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NO. 425 VOL. 50

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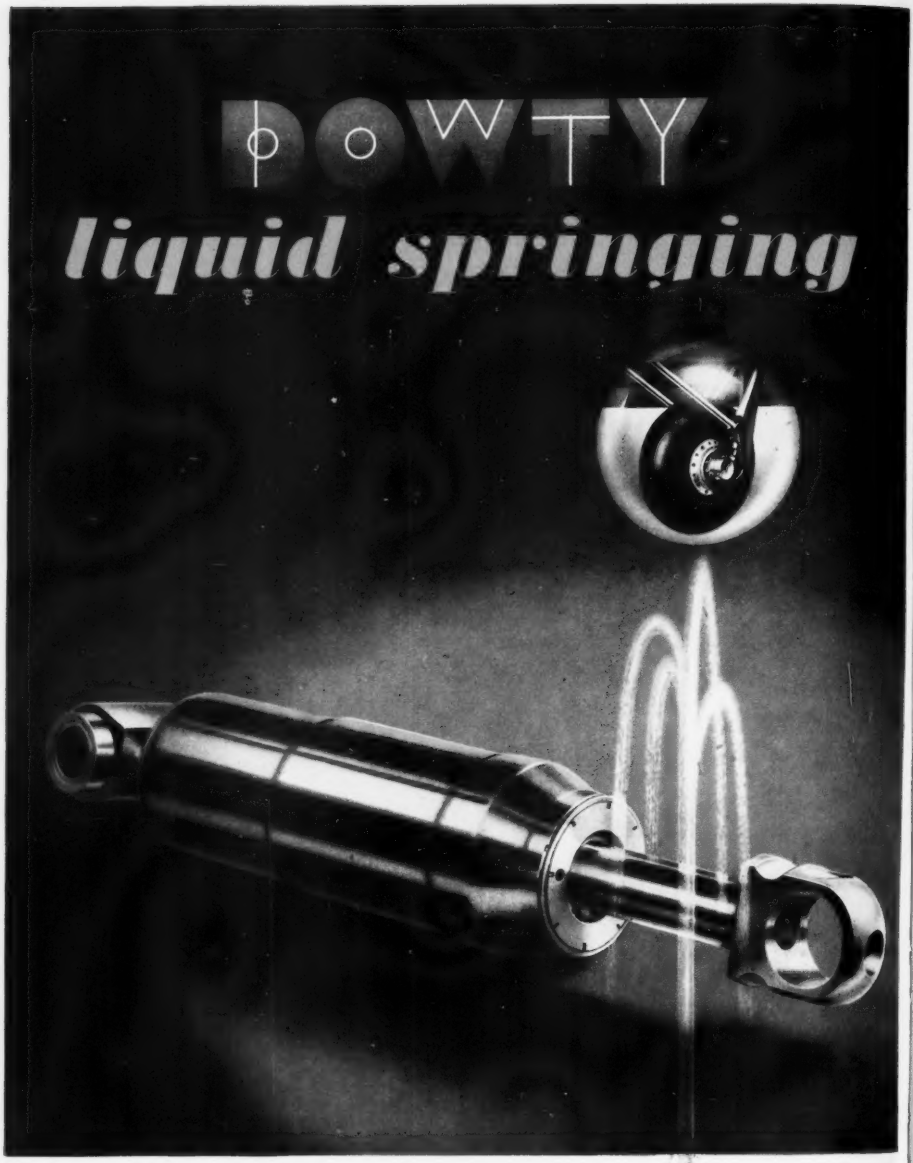

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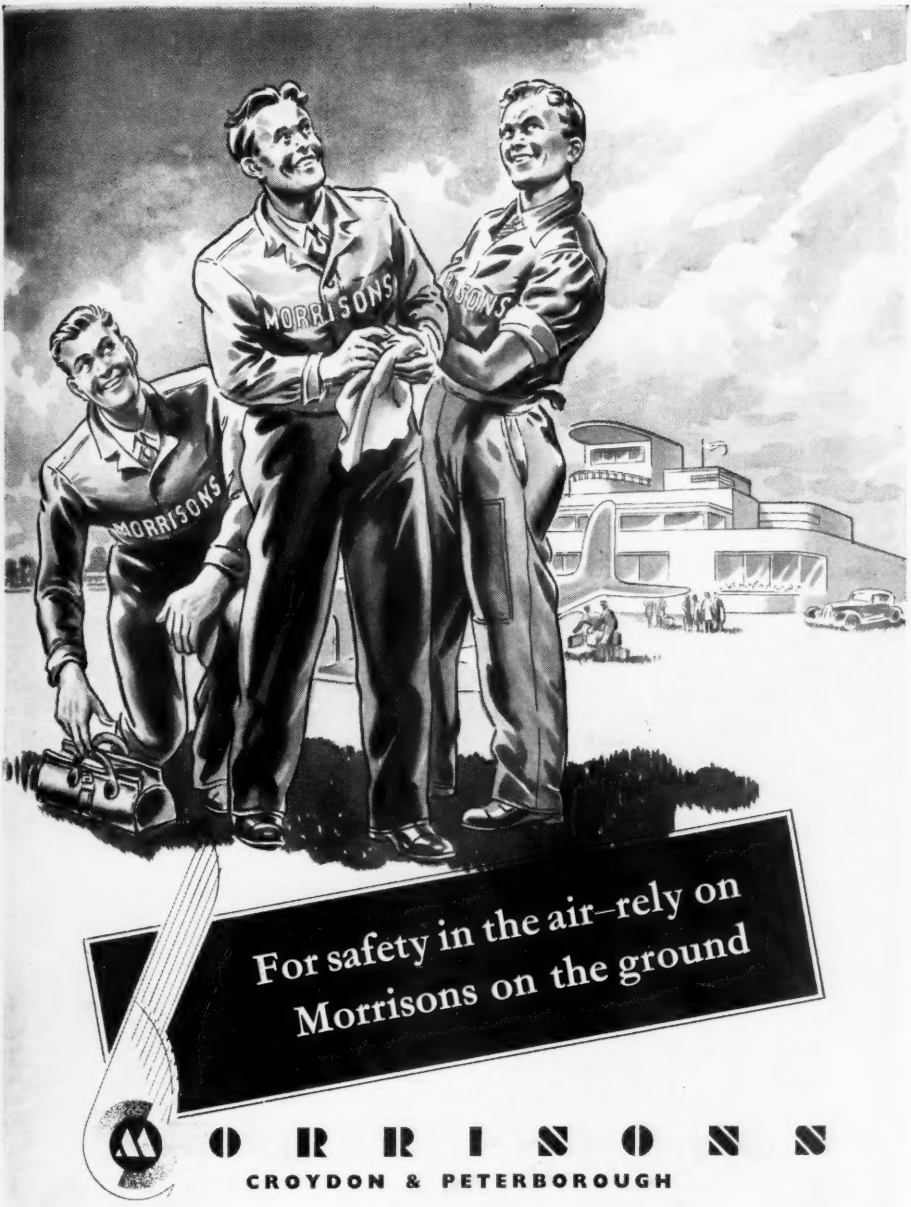

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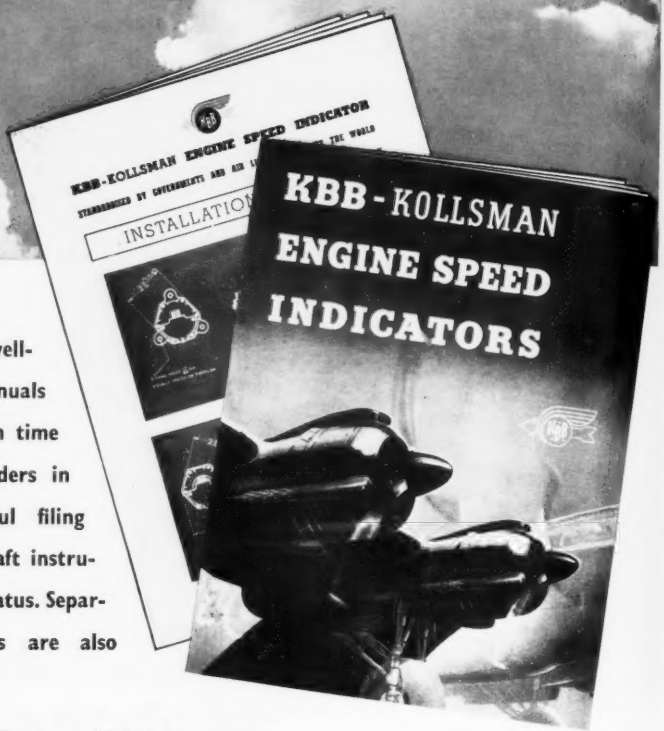

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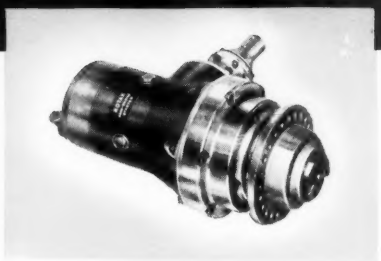

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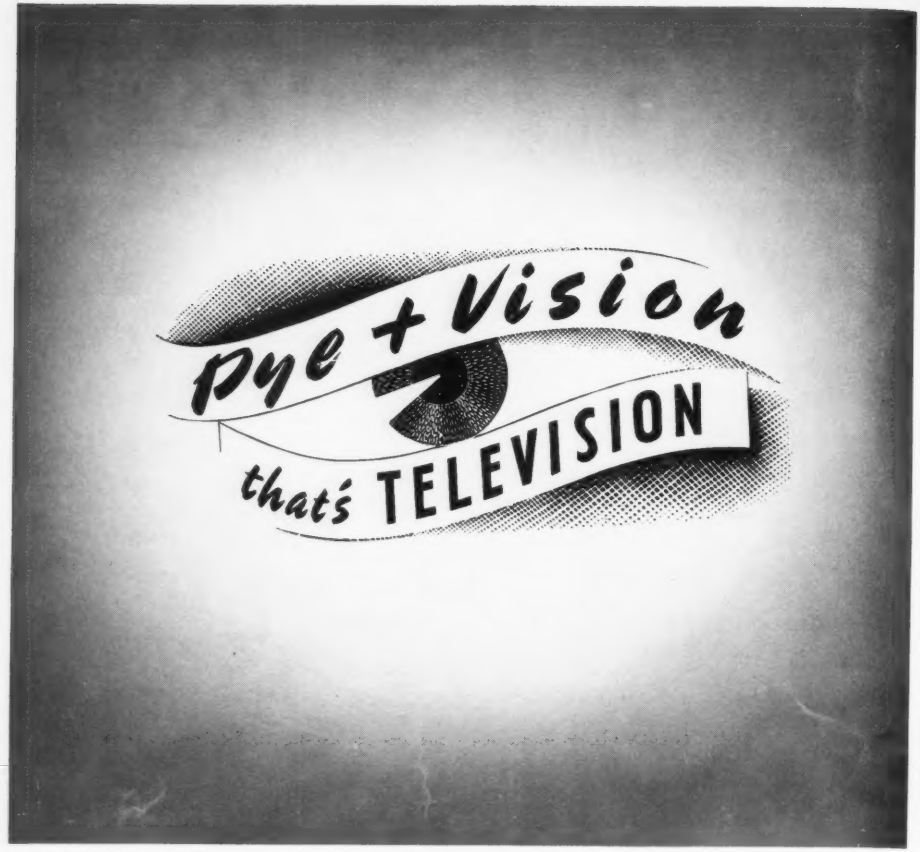

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The Journal of The Royal Aeronautical Society was founded in 1897 in succession to the Annual Reports. For the opinions expressed in Papers that are signed or initialled the authors alone are responsible. None of the papers or paragraphs must be taken as expressing the opinion of the Council of The Royal Aeronautical Society unless such is definitely stated to be the case. **The Journal is published monthly at the Offices of the Society, 4, Hamilton Place, Piccadilly, London, W.1.** Subscriptions per annum, £4 13 0 including postage; Single Numbers 7/6 or 7/9 post free. All communications for publication in the Journal, or on general matters affecting the Society should be addressed to — The Secretary, J. Laurence Pritchard, 4, Hamilton Place, W.1. The Society's Bankers are Messrs. Coutts and Co. All communications respecting Advertisement matters should be addressed to—The Advertisement Manager, Journal of The Royal Aeronautical Society, 4, Hamilton Place, W.1.

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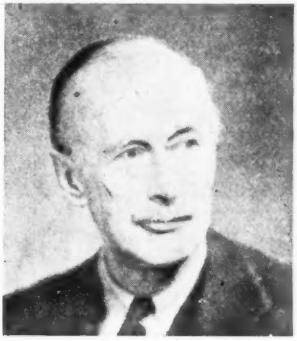
NOTE.—The President and Vice-Presidents are elected in May or June and take office in October of each year.

Dr. S. G. Hooker trained for three years under Professor L. Bairstow and for four years under Professor R. V. Southwell. He spent a year and a half at the Admiralty and Woolwich Arsenal and for the past seven years has been employed on the design and development of aero-engines with Rolls-Royce, Ltd. He is at present Assistant Chief Engineer with the Company in charge of Gas Turbines. He is an Associate Fellow of the Society.



Dr. H. R. Ricardo worked with Messrs. Rendal, Palmer and Tritton, Consulting Engineers, from 1908 to 1915. Since 1915 he has been Technical Director of Ricardo & Co., Consulting Engineers, engaged on research work in connection with internal combustion engines generally. He read the Wilbur Wright Lecture in 1930, and is a Past-President of the Institution of Mechanical Engineers. He is a Fellow of the Society.

THE GAS TURBINE DISCUSSION

THE LECTURERS

Mr. R. M. Clarkson joined the de Havilland Aircraft Co., Ltd., in 1925, and since 1941 has been Assistant Chief Engineer. He worked on the design of many de Havilland aircraft, notably the Mosquito, Hornet and Vampire. He was a member of the M.A.P. Special Projects Mission to America in 1944, and reported on American jet propelled aeroplanes. He is a Fellow of the Society.

Mr. W. G. Carter is Chief Designer of the Gloster Aircraft Co., Ltd., and was responsible for the design of the Gloster-Whittle and Meteor aircraft. He joined the Aircraft Industry in 1916 and has been connected with aircraft design ever since. He has unrivalled experience in the design of high-speed military aircraft of all types. He is a Fellow of the Society.

A FULL day discussion on gas turbines was held by the Society on the 13th March, 1946, in the Great Hall of the Institution of Civil Engineers, Great George Street, S.W.1. Four papers were presented.

Sir Frederick Handley Page, President of the Society, presided during the greater part of the proceedings.

MORNING SESSION

THE APPLICATION OF THE GAS TURBINE TO AIRCRAFT PROPULSION

by

Dr. S. G. HOOKER, B.Sc., D.I.C., D.Phil., Assoc. Fellow

1. THE WRITING ON THE WALL.

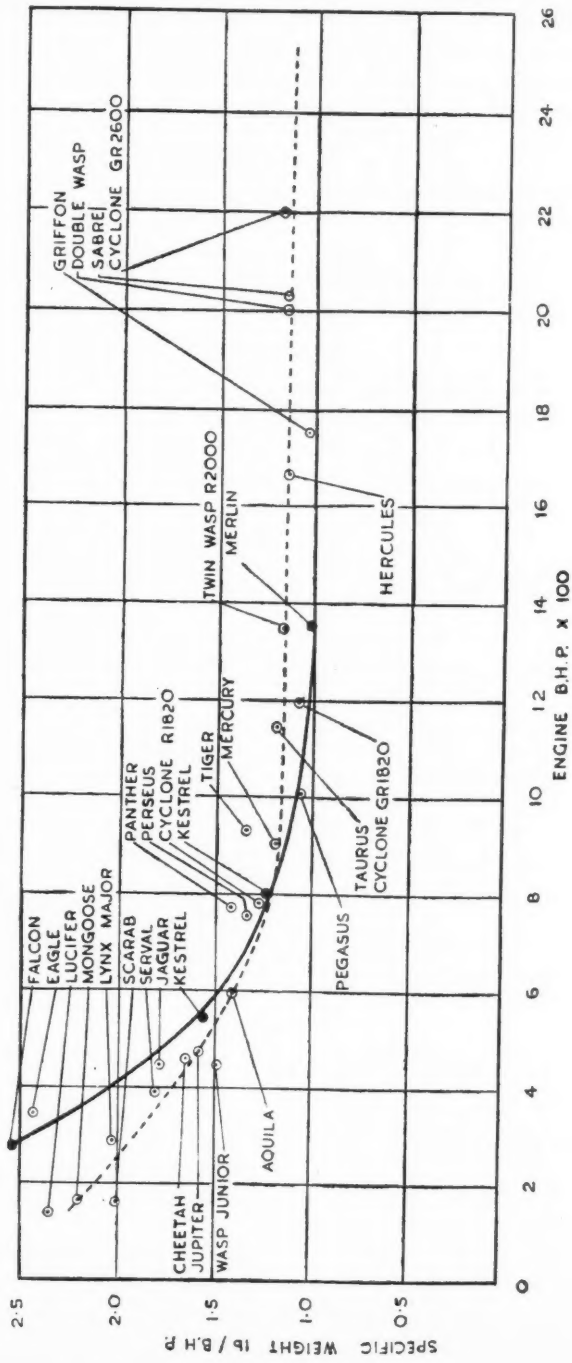
THE EVOLUTION of bigger, better and faster aircraft of all classes received a great impetus during the War period. Now, when Peace has come and the Air Age is upon us, the development of more modern aircraft both for military defensive purposes and for civil transport uses, remains a matter of urgency if Great Britain is to retain her position as a great transport power. The tempo of development reached during the War must not be slowed down if we are to keep pace with, let alone excel, the United States.

Therefore, it behoves us all to examine carefully just exactly where we are heading, and to keep our eye on the final goal rather than to be distracted into minor efforts designed to struggle along in the rear of our American rivals. In this connection, we should not become the slaves of the so-called economics of civil transport, which, in the light of the gas turbine developments are, in my view, based on debatable premises. The public demands safer, quicker and more comfortable transport, and is willing (if necessary) to pay an increased price for it. We cannot compare the economics of operation of a Rolls-Royce car with that of a horse and cart, and yet we still manage to sell not a few motor cars.

It may well be that we have already lost the immediate post-war prize to the Constellation, but that should only make us the more determined to devote every pound of our somewhat meagre finances, and every ounce of our technical effort, to the production of new types of aircraft propelled by gas turbines which will outstrip our rivals. It is to be regretted, however, that this does not appear to be our policy, and it is to be hoped that no inferiority complex will be bred in our Aircraft Industry, which, during the dire need of this Country, produced aircraft types unexcelled in any sphere of military duty.

2. THE DECLINE AND FALL OF THE PISTON ENGINE (WHITTLE).

If we examine a few of our successful war-time aircraft such as the Spitfire, Wellington, Lancaster, Halifax and Mosquito we immediately note that as far as power-weight ratio is concerned the heavy bombers fall into a class of approximately 20 lb. weight/installed cruising b.h.p.; the Mosquito about 12 lb. weight/installed cruising b.h.p.; and the Spitfire about 8 lb. weight/installed cruising b.h.p. The cruising speeds of these aircraft vary from about 180 m.p.h. for the Wellington, 220 m.p.h. for the Lancaster and Halifax, and 300-350 m.p.h. for the Mosquito and Spitfire.


SPECIFIC WEIGHT lb / B.H.P.
2·5
2·0
1·5
1·0
0·5
0
2
4
6
8
10
12
14
16
18
20
22
24
26
ENGINE B.H.P. x 100
FALCON
EAGLE
LUCIFER
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WASP JUNIOR
AQUILA

Fig. 1

Although improvements can undoubtedly be made in the streamlining of aircraft, it is clear that new advanced types will require take-off power-weight ratio of the order of 4:1 if cruising speeds in the neighbourhood of 350 m.p.h. at the normal figure of 50 per cent. maximum power are to be achieved. The problem is evidently one of the power plant, and with the conventional piston engine it is evident that the limit has been reached. Fig. 1 shows the specific weight of piston engines.

You will notice that all engines with maximum powers greater than 1,000 b.h.p. are tending to give about 1 b.h.p. per lb. of weight. Consequently, under cruising conditions of 50 per cent. power, these engines will weigh approximately 2 lb. per b.h.p. Furthermore, if we consider the installed weight of such piston engines, the picture is even gloomier, and we find that the best engines weigh approximately 3.5 lb. per installed cruising horse power. If, therefore, our final aeroplane is to weigh 8-10 lb. per installed cruising horse power, it is evident that the power plant is absorbing an undue proportion.

I need hardly remind you that the outstanding attempt at a solution of this problem of obtaining high cruising speeds with a reasonable pay load on piston engines is the de Havilland Mosquito.

Turning now to the question of power required, we note that an aircraft with an all-up weight of 100,000 lb. will require an installed take-off power of 20,000/25,000 b.h.p. if propelled by reciprocating engines. Our experience in the War has amply justified the four-engined aircraft, but a larger number of power units brings in many problems because of the complexity of the arrangement and duplication of services required by each power plant. It may well be that six separate power plants can be tolerated, or alternatively, four power plants each with two engines in Siamese twin fashion would be allowed, but in any of these cases it is clear that engines with take-off powers of 3,000-6,000 b.h.p. will be required.

There are a few types of piston engines capable of producing 3,000 h.p., but none to my knowledge which have produced 4,000 h.p. or more. Without going into great detail there are a large number of major problems in the design and development of a reciprocating aero-engine capable of exceeding 4,000 h.p. To mention a few, there is the limit to piston diameter due to detonation and heat flow into the piston itself. It is, moreover, doubtful if more than 24 cylinders can be allowed, with the increase in complexity of valve gear, bearings and ignition which is involved, together with the difficulty of cooling all the cylinders and of maintaining a uniform fuel distribution throughout the cylinders.

All these circumstances make it essential that a new type of power plant, making a complete break from the reciprocating engine, be developed, not only for high speed military types, but also for our future commercial and long-range transport machines. Such a power plant is the gas turbine engine, and we are fortunate indeed that due to the pioneer work of Air Commodore Whittle we have a flying start in the development of this unit.

No words of mine can be adequate praise for the work done by Whittle. His breadth of vision on aeronautical problems, his enthusiasm in the face of many hard setbacks, and the great technical skill with which he designed his first gas turbine, are a matter for the admiration of us all. Not only did he appreciate the advantage of the gas turbine as such, but he took in his stride the displacement of the airscrew by jet propulsion. Furthermore, he laid down the methods of performance analysis for these engines in their fundamental form, and clearly and accurately described the methods of aero- and thermo-dynamic design. It will ever redound to our discredit if we

should allow any other Nation to get ahead of us in the field of gas turbine engines for aircraft propulsion.

3. THE MECHANICAL ADVANTAGES OF THE GAS TURBINE ENGINE.

The development of gas turbines in this Country has so far been mainly concerned with the jet propulsion type. These engines have more than fulfilled all expectations, and have firmly established themselves as the prime mover for high speed fighter types. They have many advantages over reciprocating engines, and to mention a few, we have:—

1. The process of combustion being continuous the elaborate valve mechanism is removed.
2. For the same reason, magnetos and sparking plugs are not required.
3. The engine is self-cooled under all conditions.
4. The absence of reciprocating motion reduces external vibrations and eliminates many of the troubles associated therewith. Vibration problems throughout the aircraft will be diminished.
5. The absence of reciprocating motion reduces main bearing load, and makes possible and desirable the use of anti-friction bearings of the ball and roller type. These reduce the heat to oil, and thus the necessity for an oil cooler is avoided with the jet engine. The friction of the pistons on the cylinder walls being absent, mechanical losses are practically non-existent and the power output at high altitudes considerably improved.
6. Because of the continuous action of the

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DRY WEIGHT LB.	850	950	1580	1250
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MAX THRUST LB.	1600	2200	4500	4000
SPECIFIC FUEL CONS. LB/HR/LB OF THRUST	1·12	1·15	1·06	1·00
DESIGN DATE	1941	APRIL 1943	MAY 1944	JAN. 1945
DEVELOPMENT PERIOD	3 YEARS	2 YEARS	6 MONTHS	3 MONTHS
PRODUCTION COMMENCED	OCT. 1943	NOV. 1944	AUG. 1945	SEPT. 1945

Fig. 2
Rolls-Royce Engines.

gas turbine the fuel is burnt in the combustion chambers at constant pressure, and there are no peak or fluctuating pressures to be withstood. Consequently, the combustion chambers can be of a light fabricated construction, and there is no necessity for the heavy castings and liners associated with the cylinders of piston engines which have to withstand peak pressures in excess of 1,000 lb./sq. in.

7. If reduction gears and airscrews are fitted, then the smooth torque of the turbine must ultimately have a great effect in lightening the gears and the airscrew blades.
8. The stresses and heat flows in the rotating parts are amenable to analysis and rig test in scaled form, thus adding to the speed and certainty of development.

Unlike piston engines, each of which seems to have its own personal and particular mechanical problems, jet propulsion units behave far more reasonably, and once a typical turbine problem has been solved for one engine, then it can be regarded as solved for all turbine engines of that type. As an illustration of the value of this, Fig. 2 compares the development periods of the jet engines which have so far been developed by Rolls-Royce, Ltd.

Whereas the reciprocating engine had a development period of from five to ten years, it is now clear that a similar state of mechanical reliability can be reached on jet propulsion units in about one to two years.

4. PISTON VERSUS TURBINE.

I should now like to illustrate the close analogy which exists between a gas turbine engine and an ordinary reciprocating engine. You will notice that in Fig. 3 a propeller is included in the arrangement of the gas turbine, although at the moment we are used to thinking of these engines as confined solely to jet propulsion. The only real difference between the two engines shown is that the turbine is replaced by a piston which also gives the major portion of the compression of the gases. Both engines consist basically of a compressor, a combustion chamber and an exhaust system with, on the one hand, a turbine to produce the power, and on the other hand, a piston. The advantages of the gas turbine for producing power can be briefly summarised as follows:—

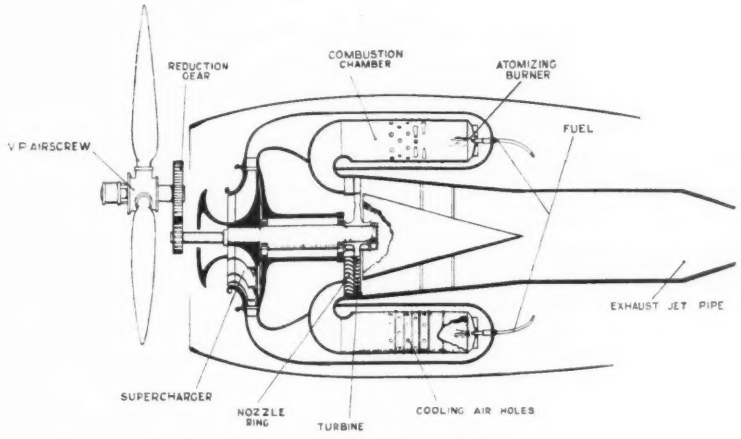
1. Combustion being continuous at relatively low constant pressures, there are no peak and fluctuating pressures, and hence the necessity for high octane fuels to control detonation is removed. Practically any form of liquid fuel could be used, provided that it is clean and does not freeze (or boil) at altitude.
2. With a four-stroke engine, only one quarter of the time is used for the production of power, the other three-quarters are employed in the charging, compressing and exhausting phases. The very fact of arresting the charge in the cylinder while it is compressed and heated imposes a limitation upon the volume of air which the piston engine can consume, particularly when one takes into account the added fact that the piston speed is also limited for other mechanical reasons. Hence, for a given power output the gas turbine with its continuous output is smaller and lighter than the reciprocating engine.
3. Gas turbines function on combined aero- and thermo-dynamic principles. It is desirable that the air should flow through the engine at very high velocities and this again reduces the size of the engine for a given power output.
4. The continuous cruising output of gas turbines can be a very large proportion of the maximum power.

Some relative figures on the above points may be of interest. A supercharged reciprocating engine of the Merlin size develops

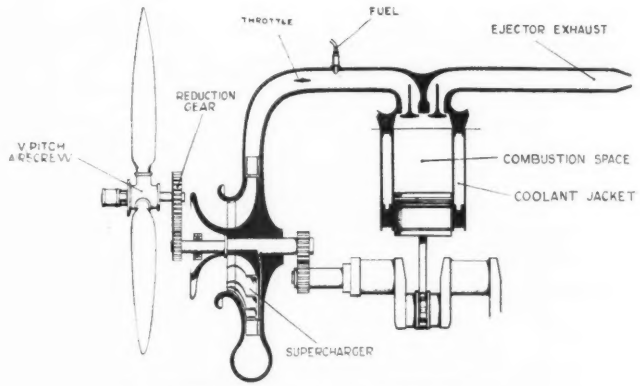
about 1,000 b.h.p. for an air consumption of 120 lb./min. Hence, each lb. of air consumed per second yields 500 b.h.p. which with an airscrew efficiency of 80 per cent gives 400 thrust h.p.

The Derwent V jet engine on the World's Record runs at 600 m.p.h. consumed $2\frac{1}{2}$ tons of air per minute or nearly 86 lb./sec. Under this condition, the engine produced about 5,000 thrust h.p., *i.e.*, about 60 thrust h.p. per lb. of air consumed per second.

Thus, a piston engine produces about



DIAGRAMMATIC ARRANGEMENT
OF INTERNAL COMBUSTION TURBINE



DIAGRAMMATIC ARRANGEMENT
OF INTERNAL COMBUSTION RECIPROCATING ENGINE

Fig. 3

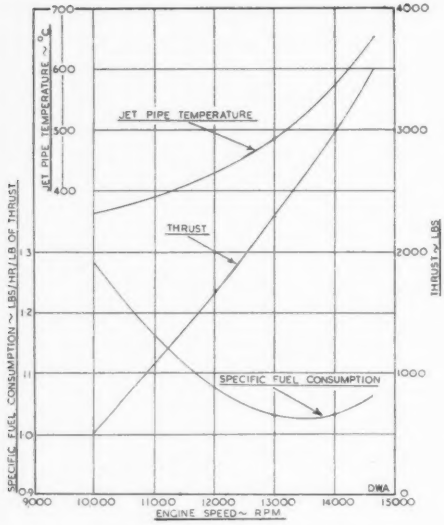


Fig. 4
Test Bed Performance of Derwent V Engines.

seven times as much power out of every lb. of air consumed in unit time, as a gas turbine engine. On the other hand, a gas turbine engine of comparable size and bulk will consume more than 40 times the air of the comparable reciprocating engine, and thus the balance of power remains about six-fold in favour of the gas turbine.

The operational limitations on a piston engine are r.p.m. and boost pressure, whereas the corresponding limitations on a jet engine are r.p.m. and jet pipe temperature—the former because of the very high stresses in the rotating parts, and the latter because of the strength of available materials at the high temperatures which are used.

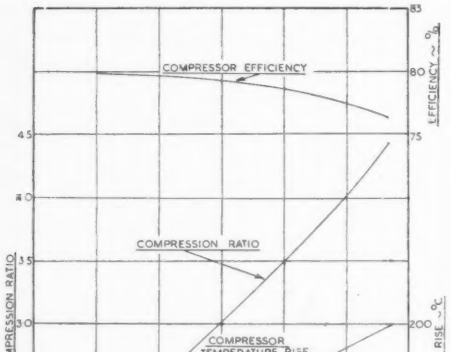


Fig. 5
Test Bed Performance of Derwent V Engines.

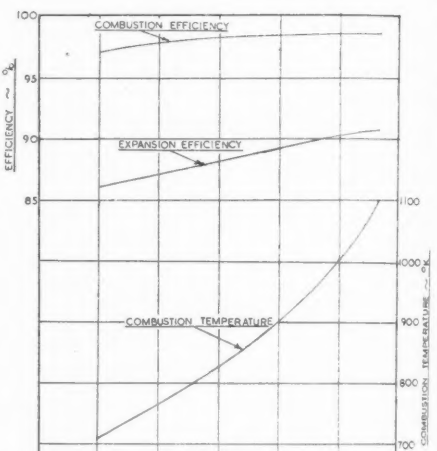


Fig. 6
Test Bed Performance of Derwent V Engines.

A typical test bed performance of a single-stage centrifugal jet engine such as the Derwent V is shown in Fig. 4. You will notice that the highest temperature shown is between 650° and 700°C. This represents the limit to which present day materials can be used for turbine blades in this type of engine, although other types can be designed with lower turbine blade stresses, and better materials are being evolved which will allow higher temperatures to be used in the future.

It is of interest to note that from 11,500

r.p.m. to 15,000 r.p.m. the specific fuel consumption only varies about 7 per cent. In other words, the specific consumption is fairly constant from 1,500 lb. to 4,000 lb. of thrust.

In Figs. 5 and 6 the performance of the engine is broken down to give the figures for each component. To interpret the performance of this jet engine in terms of that of the equivalent piston engine delivering brake h.p., we have to take into account the efficiency of the propeller which it is necessary to use with the latter type of power plant. The equation relating the performance of a jet engine to that of its equivalent piston engine is

$$\frac{TVa}{\eta a} = \text{b.h.p.}$$

Where T is the thrust of the jet engine,

Va is the forward speed of the aircraft.

ηa is the efficiency of the airscrew at speed Va,

B.h.p. is the power of the equivalent power plant.

Now, at forward speeds of 600 m.p.h. the airscrew efficiency will probably not exceed about 53 per cent. due to compressibility losses on the blades. Using this value for ηa in the above equation we find that at 600 m.p.h. 1 lb. of thrust is equivalent to 3 b.h.p. (or, alternatively, 3 b.h.p. is required to produce 1 lb. of thrust). Consequently, on the record runs the Derwent V engines were producing the equivalent of approximately 10,000 h.p. each, and the Meteor aircraft had a total installed equivalent power of about 20,000 h.p.

Referring to the specific consumption of the engine in Fig. 1 and making allowances for the effect of a forward speed of 600 m.p.h. on the engine fuel consumption, each lb. of thrust requires a fuel consumption of about 1.5 lb. of fuel per hour. Since each lb. of thrust is worth 3 b.h.p. it follows that the equivalent fuel consumption of the engine is approximately 0.50 lb. per b.h.p.—a figure which cannot be approached by reciprocating engines at full power and the necessary rich mixture.

A few leading particulars of the Rolls-Royce Derwent V engines are :

Weight, 1,250 lb.

Diameter, 43 ins.

Overall length, excluding jet pipe, 83.1 ins.

It is worth noting that the weight of 1,250 lb. for an equivalent h.p. of 10,000, or a specific weight of 0.125 lb. per equivalent b.h.p., is only $\frac{1}{8}$th that of the conventional reciprocating engine. The moral of this is that at speeds in excess of approximately 500 m.p.h. the simple single stage jet propulsion engine is far better than the reciprocating piston engine for aircraft propulsion, and is just as economical. Its overall fuel consumption is larger, simply because it produces enormous power for its small bulk and weight.

On the other hand, at 300 m.p.h. forward speed, the thrust of the engine is about 2,900 lb. and the fuel consumption is 475 gallons per hour, since at this speed 1 lb. of thrust is equal to 1 b.h.p. (taking an airscrew efficiency of 80 per cent), it follows that the specific consumption of the engine is equivalent to 1.24 lb. of fuel/b.h.p./hr. which is more than twice that of the reciprocating engine. On the score of weight, however, the jet engine still has a handsome advantage weighing only 0.43 lb. equivalent b.h.p.

In considering the gas turbine engine we must take into account the rate of progress on these units and Figs. 7 to 9 indicate the trend in respect to the specific weights of the units, the specific fuel consumption of the units and the thrust per sq. ft. of frontal area. Provided that financial support is forthcoming and the war-time rate of development is maintained, we can confidently look forward to continued progress which will have far-reaching

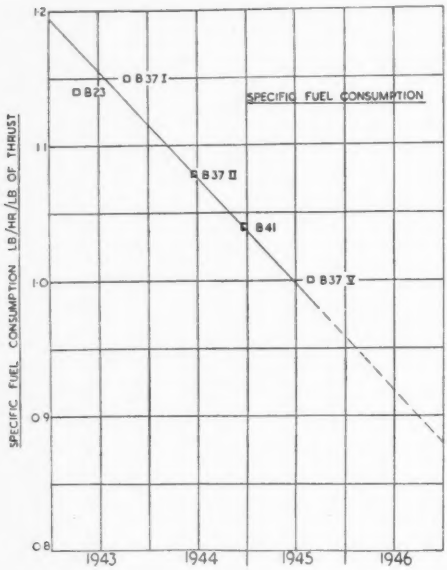


Fig. 7
Past and Estimated Future Rate of Progress on Jet Units.

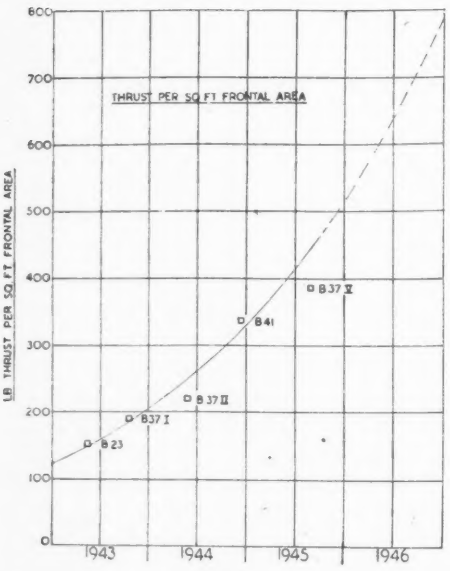


Fig. 8
Past and Estimated Future Rate of Progress on Jet Units.

reactions upon aircraft design. In this connection a difficulty arises in the timing of the final marriage of the aircraft and the engines. Before a large modern aircraft can be designed and made, several generations of gas turbines may have become obsolete, and therefore, it behoves us to be bold and optimistic in our outlook on aircraft.

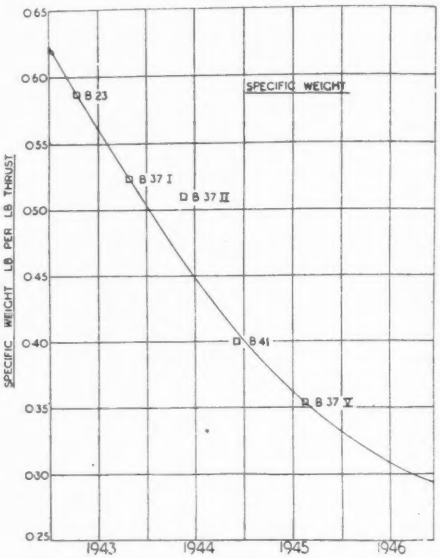


Fig. 9
Past and Estimated Future Rate of Progress on Jet Units.

5. JET VERSUS AIRSCREW.

Aircraft propulsion by airscrews having been the practice up to now, I feel that we are all inclined to accept this means of propulsion without examining the price we have to pay at aircraft speeds exceeding 400 m.p.h.

Figure 10 shows the power required for level flight at sea level against aircraft speed, the machine chosen being a typical fighter requiring 1,000 h.p. to do 300 m.p.h. You will note that at 500 m.p.h. the thrust h.p. required by the aeroplane is 5,000, whereas we must apply 7,500 h.p. to the propeller in order to obtain this. The wasted 2,500 h.p. is about equally divided between normal

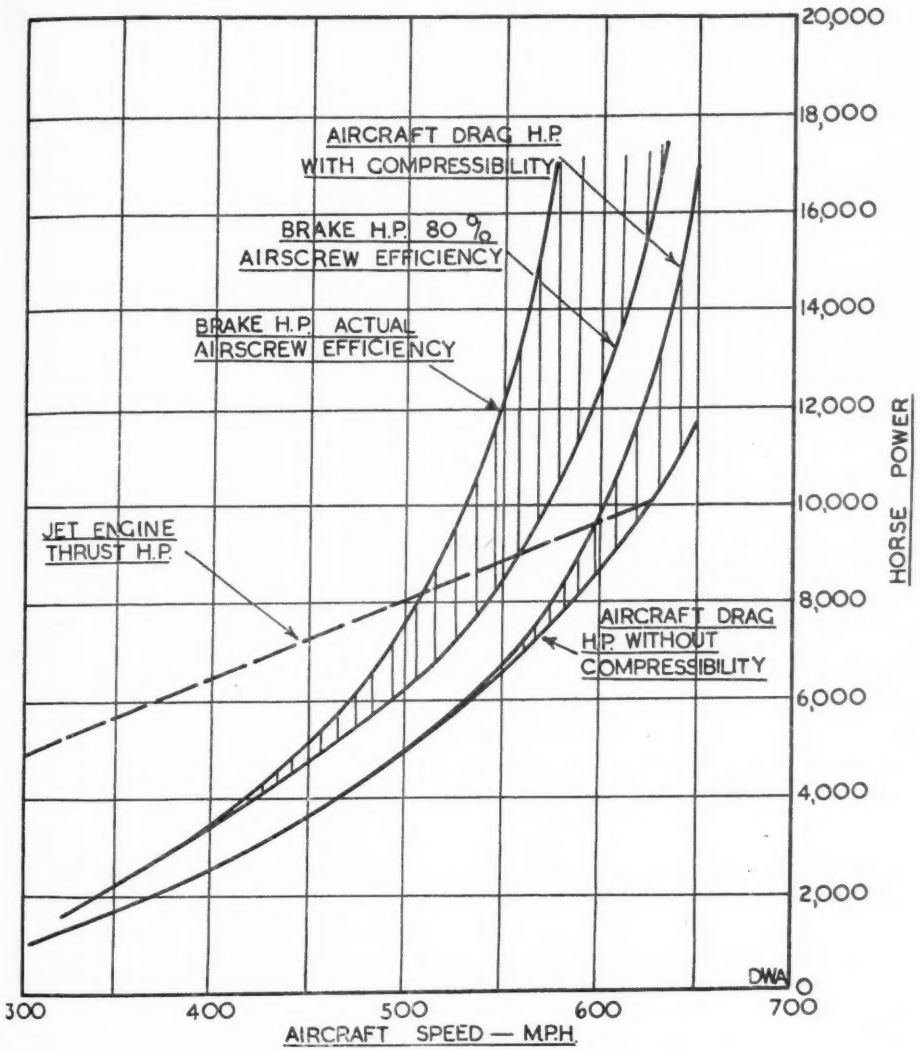


Fig. 10
Power Required for Level Flight at Sea Level.

rotational and drag losses on the propeller blades and compressibility effects on the blade tips. As the aircraft speed is increased the losses due to compressibility assume a very high proportion indeed, and although compressibility losses can be modified by changes in blade shape and solidity of the airscrew this will carry with it a heavy weight penalty. In addition, a large proportion of the compressibility losses will go into noise and will necessitate heavy silencing in the cabin to obtain a tolerable level for the passengers.

Figure 11 shows a comparison between airscrew efficiency and jet propulsion efficiency. At 300 m.p.h. the airscrew efficiency is

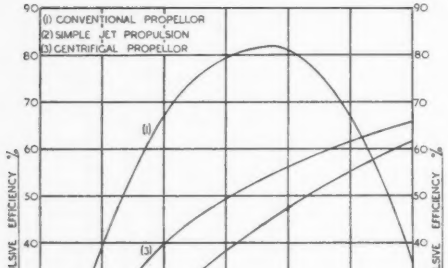


Fig. 11

Propulsive Efficiency v. Aircraft Speed.

double that of the jet and this largely accounts for the fact that the fuel consumption of the jet engine is more than double that of the piston engine at this condition. At 550 m.p.h. the jet and the airscrew are equally efficient, and since the jet is so much simpler and lighter than the airscrew it follows immediately that jet propulsion must be best at this speed. After all, there is no essential difference between jet propulsion and airscrew propulsion. The airscrew collects a large mass of air and blows it backwards relatively slowly. In order to do so, it must exert a rearward thrust upon the air with the natural reaction that the airscrew itself has an equal thrust forwards, to overcome the aircraft drag. The jet, on the other hand, blows a relatively small mass of air backwards at very high speeds and thus produces a thrust in the opposite direction upon the aircraft. It should be remembered that the thrust from the backward moving gases is given by the product of their mass multiplied by their velocity; that is to say, one can generate the same thrust by having a large mass at low velocity, or a small mass at high velocity. But it should also be remembered that the kinetic energy associated with this jet velocity is all wasted since the air or gas blows away into the atmosphere, and since the energy which is wasted depends upon the mass of gas multiplied by the square of the velocity, it follows that the jet with its higher velocities wastes more energy than the airscrew and is, therefore, less efficient.

This situation changes, however as the aircraft speed increases, because although the jet continues to issue at high speeds from the engine yet relative to the surrounding atmosphere, its absolute velocity is less by the forward speed of the machine, and consequently the kinetic energy wasted diminishes as the aircraft speed increases. In the theoretical examples shown in Fig. 3 the airscrew and the jet are equally efficient at 540 m.p.h. This is not the whole story, however, because the airscrew is a heavy piece of mechanism and its weight is associated with a certain drag on the aircraft, and this drag must, therefore, be deducted from the useful thrust which the propeller produces. In ad-

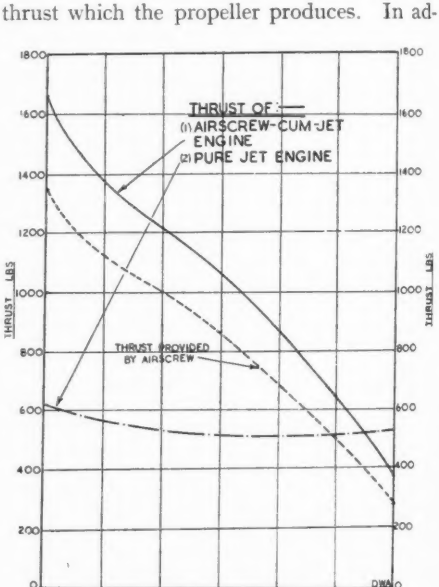


Fig. 12

Comparison of Pure Jet Engine and Airscrew-cum-Jet Engine.

Gas Horse Power of both Engines under Static Conditions = 1,000.

dition, the airscrew blows a slip-stream over the wings or fuselage of the machine which again produces an adverse drag. Consequently, the practical crossover between the airscrew and the jet occurs at a lower speed, probably in the region of 500 m.p.h.

It is apparent, therefore, that if we are going to consider aircraft in the speed range of 300 to 450 m.p.h. it will always pay, so far as the total fuel consumed is concerned, to propel the machine by an airscrew and not by jets. As explained earlier, there is no reason why gas turbine engines should not be fitted with airscrews, so let us consider the way of doing this a little more closely. First of all, we can regard the original jet engine as something like a boiler. It produces at exit from the turbine, hot gas under pressure.

Now, this hot gas can either be squirted out of a pipe in the form of a jet as for jet propulsion, which is simple, light, efficient at high speeds, but inefficient at low speeds, or, on the other hand, this hot gas under pressure can be passed through another turbine and made to develop power to drive an airscrew which is more complicated, heavier, efficient at low speeds but inefficient at high speeds due to compressibility effects upon the blade tips.

It is clear, therefore, that the choice as to whether jet propulsion or airscrew propulsion is the better depends entirely upon the duty the aircraft has to perform.

Let us again return to the comparison between a jet engine and an airscrew jet turbine. Fig. 12 shows the comparison between two engines, each of which produces 1,000 gas h.p. when regarded as a boiler. If this hot gas be released as a jet, the thrust obtained will be between 500 and 600 lb. depending on the aircraft speed. If, however, 75 per cent. of this gas h.p. is put into an airscrew by means of another turbine and the rest left as a jet, the thrust obtained will be very much increased except at speeds greater than 550 m.p.h. For example, at 300 m.p.h. the total thrust from the airscrew combination will be double that given by the jet, which is really another example of the fact that the airscrew is twice as efficient as the jet at this speed.

I may appear to have stressed the differences between airscrew and jet propulsion rather much in the preceding examples. I have done this because I am sure that you are all well aware that the criticism of high fuel consumption is continually levelled at gas turbine engines. This criticism is only justifiable for aircraft speeds less than about 450 m.p.h., since at speeds greater than this the jet is as efficient as the airscrew, and the overall thermal efficiency of the gas turbine-cum-jet combination is equal to the overall thermal efficiency of the piston engine-cum-propeller combination. In the speed range of less than 450 m.p.h. there is no need for the gas turbine engine to suffer the disadvantages of jet propulsion, and an immediate palliative can be obtained by fitting an airscrew to a gas turbine engine as has been done in the case of the Rolls-Royce Trent engine shown in Fig. 13.

Two of these engines have been fitted to the modified Meteor aircraft shown in Fig. 14.

6. EFFECT OF COMPRESSION RATIO.

I do not wish to convey that the only reason for the high fuel consumption of present turbine engines is the inefficiency of the jet, because there is another reason which is equally obvious. I refer to the compression ratio of the engine, with its effect upon the thermal efficiency of the cycle employed. In a supercharged piston engine the charge is compressed through a volume ratio of 6:1 in the cylinder itself, giving an overall compression ratio of 10:1 approximately, due to the almost adiabatic compression by the piston. On single stage gas turbines, however, the compression ratio is limited to about 4:1, and you are all well aware that low compression ratio engines have high fuel con-

Fig. 13

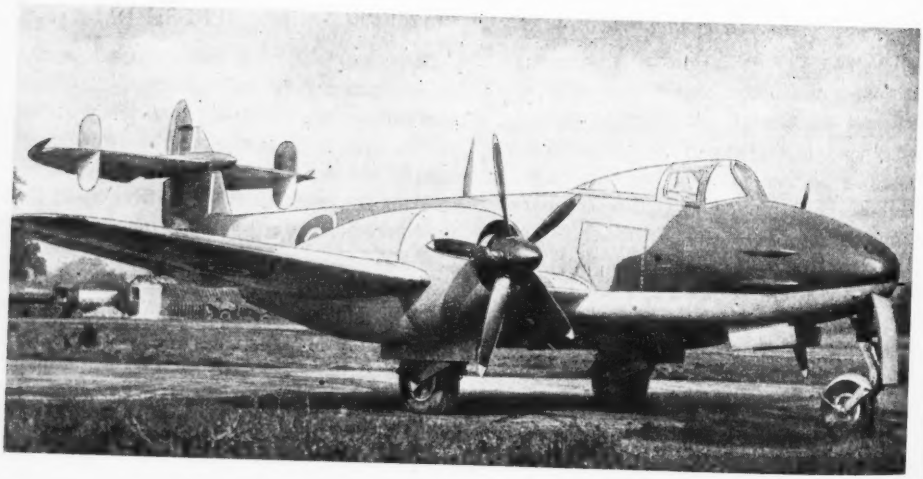


Fig. 14

sumptions. Another important point is that in a piston engine the compression ratio is independent of the engine r.p.m., being dependent on the stroke of the piston only; but in a turbine engine the compression ratio varies rather more than the square of the r.p.m.

It follows, therefore, that our next attack on the fuel consumption of turbines must be made by increasing the maximum compression ratio of the cycle, and this can evidently be done by replacing the single stage compressor by a two stage or a multi stage axial compressor. Now it would be useless to increase the compression ratio of the engine without maintaining the compressor efficiency, for otherwise the advantage of the high compression ratio would be lost by the fact that too much power would be absorbed by the compressors. To get the full advantage we must, therefore, increase the compression ratio of the engine and maintain the overall compressor efficiency at the same time.

Fig. 15 shows the compressor efficiency which, with modern knowledge, one might expect to get by utilising combinations of two stage centrifugals, axial-cum-centrifugals, or multi stage axial compressors. Please notice that at 6:1 compression ratio the corresponding temperature rise is roughly 250°C. as these figures will be important to our next slide. Also please note that as

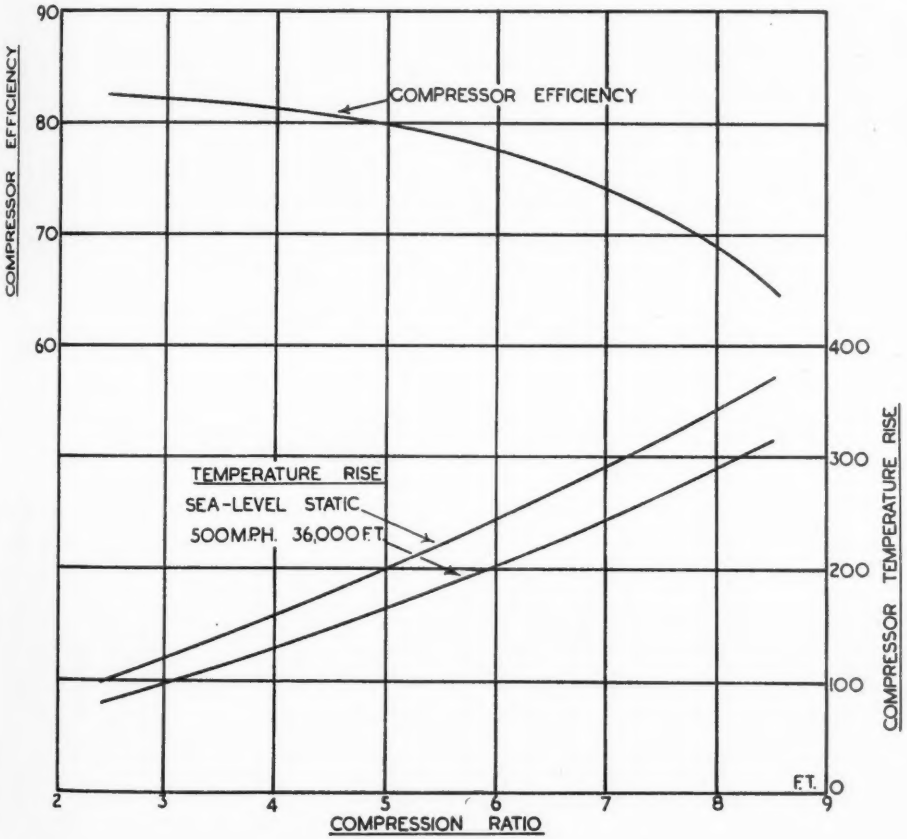


Fig. 15
Compressor Performance.

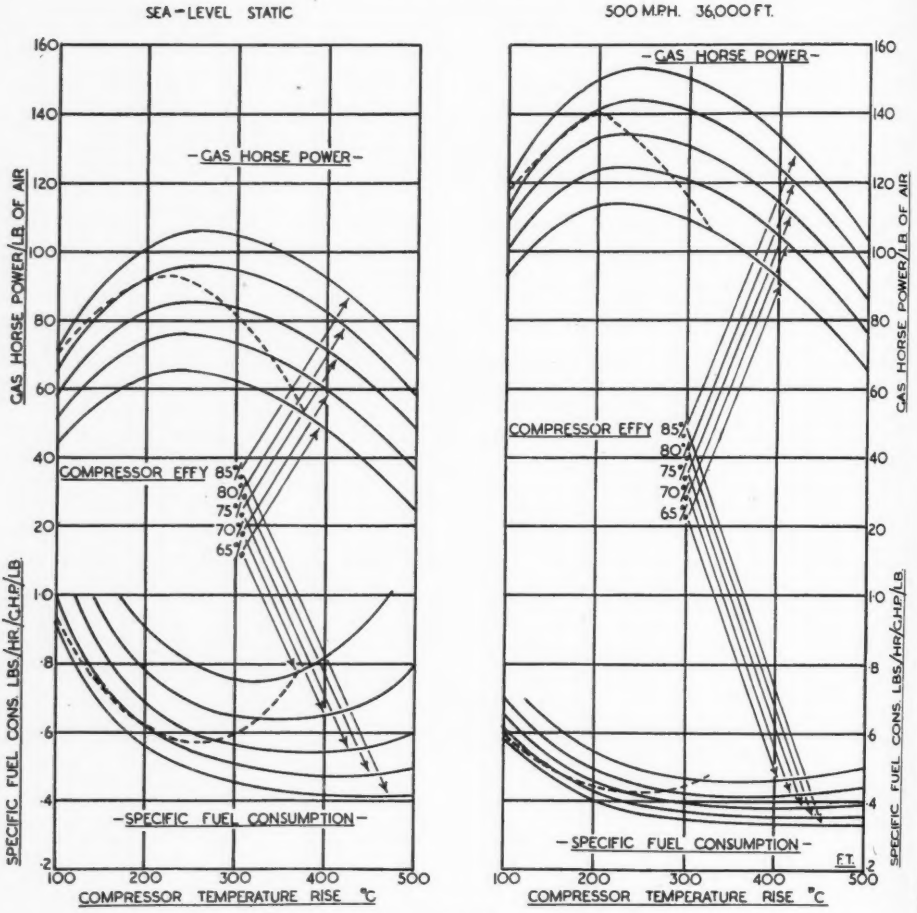


Fig. 16
Variation of Compressor Efficiency.
Expansion Effy. = 90%. Combustion Temp. = 1100°K.

the compression ratio or temperature rise through the compressor is increased, the efficiency falls, being 80 per cent. at 5 : 1 compression ratio or 200°C. temperature rise, and 75 per cent. at 7:1 compression ratio or 290°C. temperature rise.

Still regarding the gas turbine as a boiler, Fig. 16 shows the effect of compressor efficiency upon the gas h.p. available per lb. of air passing through the engine, and also the fuel consumption in lb. per hour per gas h.p.

Each curve refers to a particular constant compressor efficiency, and the basic scale is compressor temperature rise. Ignoring the dotted curve, it would appear that whatever the efficiency of the compressor, the maximum power per lb. of air will be obtained with a temperature rise through the compressor of 250°C. On the other hand, the minimum fuel consumption will be obtained at much higher temperature rises, and the required temperature rise for minimum consumption will increase as the compressor

efficiency increases. However, this is not the whole story, because one cannot keep increasing the temperature rise through a compressor and maintain the efficiency of the compression constant.

As the compression ratio or the temperature rise increases, so the efficiency of compression will fall as shown on the preceding figure. Consequently, if we relate on the curves shown on Fig. 16 the points of efficiency and temperature rise as shown on Fig. 15, we obtain the dotted curves as being the practical envelope of what we can do, and it is clear that both the maximum power and minimum fuel consumption will occur when the temperature rise through the compressor is approximately 250°C., and this, as pointed out earlier, corresponds to a compression ratio of 6:1. Let me make this point clear. It does not pay to increase continually the compression ratio of a gas turbine engine because the efficiency of compression is falling and there appears to be little purpose in going beyond 6 or 7:1 compression ratio at sea level.

Let us consider the effect of a two stage compressor at 6:1 compression ratio upon the performance of a jet propulsion engine. This is shown in Fig. 17.

Both engines have the same static take-off rating of 5,500 lb. thrust. The performance of the two stage engine is shown by the dotted grid, and if as a numerical example we consider the case of 400 m.p.h. at 20,000 ft., then the two stage engine gives a thrust of 2,900 lb. with a fuel consumption of 1.09 lb. of fuel per lb. of thrust per hour, while the single stage engine gives the same thrust

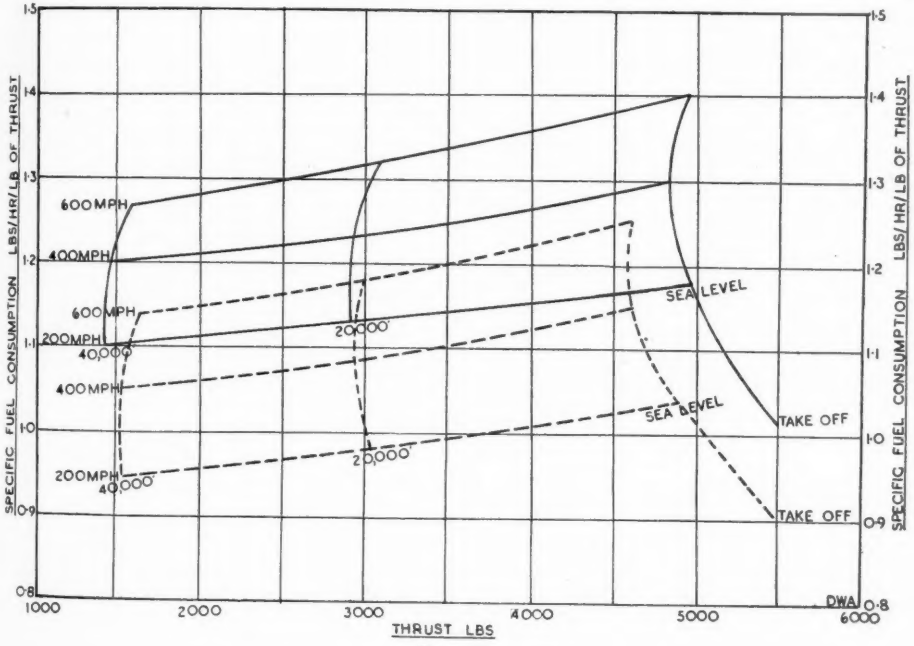


Fig. 17

TWO-STAGE v. SINGLE-STAGE JET PROPULSION ENGINE.

Specific Fuel Consumption—Thrust.

——Rolls-Royce Nene Engine (Single-stage)
Weight 1,600 lb.
Diameter 49.5 in.
Length 96.8 in.

- - - -Rolls-Royce/B42 Two-stage Engine
Weight 1,500 lb.
Diameter 43.5 in.
Length 106 in.

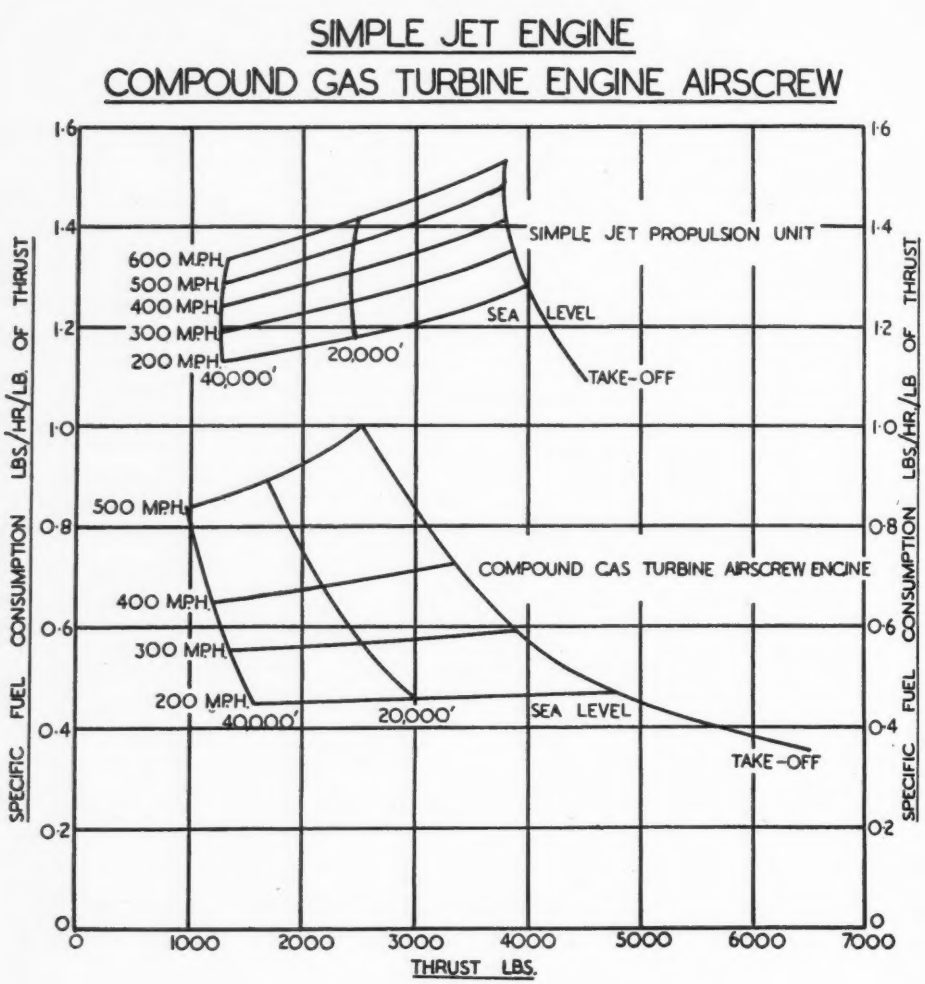


Fig. 18

but its fuel consumption is 1.23 lb. of fuel per lb. of thrust per hour. That is to say, the two stage engine shows an improvement of roughly 14 per cent. in fuel consumption. Since in a two stage engine the gases are compressed more, it follows that the diameter of the engine will be smaller than that of a single stage for the same thrust.

Now, let us consider the effect of combining both a two stage compressor and an airscrew upon the performance of a gas turbine engine. This is shown in Fig. 18.

The comparison shown is that of a single stage jet propulsion engine against a two stage compound engine with airscrew. Again, choosing as a numerical example 400 m.p.h. at 20,000 ft. we see that the jet propulsion engine produces 2,400 lb. of thrust with a fuel consumption of 1.3 lb. of fuel per lb. of thrust per hour, whereas the compound engine produces 2,200 lb. of thrust with a fuel consumption of .67 lb. fuel/lb. of thrust /hour, i.e., the fuel consumption has now been practically halved.

As a matter of interest, let us examine the performance of the compound engine at 300 m.p.h. because we know that at this speed, lb. of thrust and equivalent b.h.p. are identical. At sea level the engine produces 3,900 b.h.p. with a fuel consumption of .58 lb. per b.h.p. At 20,000 ft. the figures are 2,500 b.h.p. with a fuel consumption of .56 lb. per b.h.p. per hour, while at 40,000 ft. we have 1,300 b.h.p. and .55 specific fuel consumption figures, which are very good judged by the best of piston engine performances, particularly when one takes into account that there is no main engine cooling required on gas turbine engines.

7. EFFECT OF COMBUSTION TEMPERATURE.

All of the preceding examples have been worked out on the basis that the maximum combustion temperature at entry to the turbine is 1,100°K. This temperature is very close to the maximum which the turbine

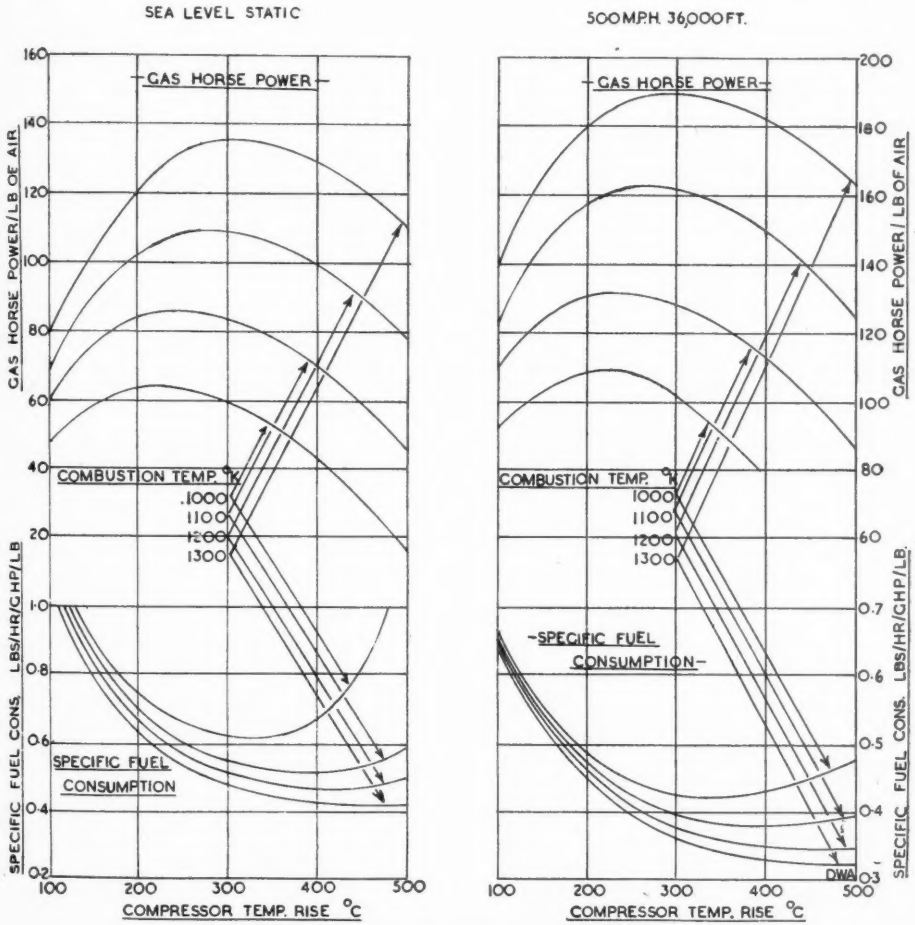


Fig. 19
Variation of Combustion Temperature.
Compressor Effy. = 75%. Expansion Effy. = 90%.

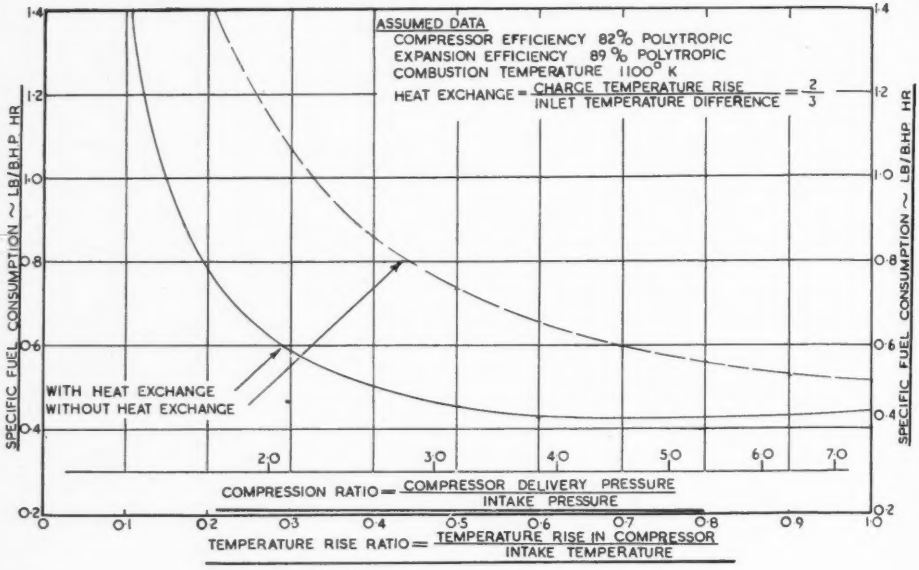

ASSUMED DATA
COMPRESSOR EFFICIENCY 82% POLYTROPIC
EXPANSION EFFICIENCY 89% POLYTROPIC
COMBUSTION TEMPERATURE 1100° K
HEAT EXCHANGE = CHARGE TEMPERATURE RISE / INLET TEMPERATURE DIFFERENCE = 2/3
SPECIFIC FUEL CONSUMPTION ~ LB/B.H.P. HR
WITH HEAT EXCHANGE
WITHOUT HEAT EXCHANGE
COMPRESSION RATIO = COMPRESSOR DELIVERY PRESSURE / INTAKE PRESSURE
TEMPERATURE RISE RATIO = TEMPERATURE RISE IN COMPRESSOR / INTAKE TEMPERATURE

Fig. 20
Effect of Heat Exchange on Fuel Consumption.

blades in Nimonic 80 can withstand at the stresses of a modern gas turbine engine. The difficulty is that under the high temperature and stress conditions, the turbine blades "creep," and since the clearance between the tips of the blades and the casings must be kept small for efficiency reasons, very little extension in the blades can be tolerated. Better turbine blade materials are in hand, and recourse can be had to such devices as water cooling or air cooling the blades, and under these conditions, high combustion temperatures can be allowed. It is of interest to examine the effect of combustion temperature upon performance of a gas turbine engine. This is shown in Fig. 19.

It is very clear that flame temperature has a very important effect upon the gas h.p./lb. air/sec. available in the jet pipe, for example, the figure illustrates that increase in the flame temperature from 1,000°K. to 1,300°K. more than doubles the power output of the engine for each lb. of air consumed per second. Again, the optimum power occurs at about 250°C. temperature rise through the compressors. The effect upon the fuel consumption of the engine is no less marked, and the specific consumption falls from about .65 lb./hr./g.h.p. to about .53 lb./hr./g.h.p.

It is also evident that the higher the combustion temperature employed, the higher the compression ratio required for the minimum fuel consumption. But clearly the main effect of combustion temperature is on the power output of the engine. Since the great advantage of gas turbine engines is their large power output for a minimum bulk and weight, it is clear that a steady increase in flame temperature will be an important feature in development of new gas turbine types.

8. THE EFFECT OF HEAT EXCHANGE ON FUEL CONSUMPTION.

Since the only source of heat and power in the engine is the fuel, it follows that the hot gases which are discharged to the atmosphere, constitute a waste of fuel. A certain

amount of this wastage can be recovered by means of a heat exchanger which functions in the following manner. After compression in the compressor, the air is circulated through a radiator or heat exchanger situated in the jet pipe of the engine. By this means, heat from exhaust gases is transmitted to the compressed air, and consequently, less fuel has to be added to the compressed air in order to reach the limiting operating temperature.

In the case of the example shown in Fig. 20, it is assumed that two-thirds of the temperature difference between the compressed air and exhaust gases can be exchanged, and it can be seen that the effect upon the fuel consumption of the engine is very marked, for example, in the case of the engine without the heat exchanger, as the compression ratio changes from 3.5 : 1 to 7 : 1 the fuel consumption falls from about .7 lb./g.h.p./hr. to .5 lb./g.h.p./hr., whereas with the same range of operation, on the engine fitted with a heat exchanger, the fuel consumption remains practically constant at .43 lb./g.h.p./hr. In other words, the addition of a heat exchanger not only reduces the fuel consumption but it also allows the engine to be operated over a wide range of powers without appreciably affecting the specific fuel consumption. Thus, in the case of an engine fitted with a

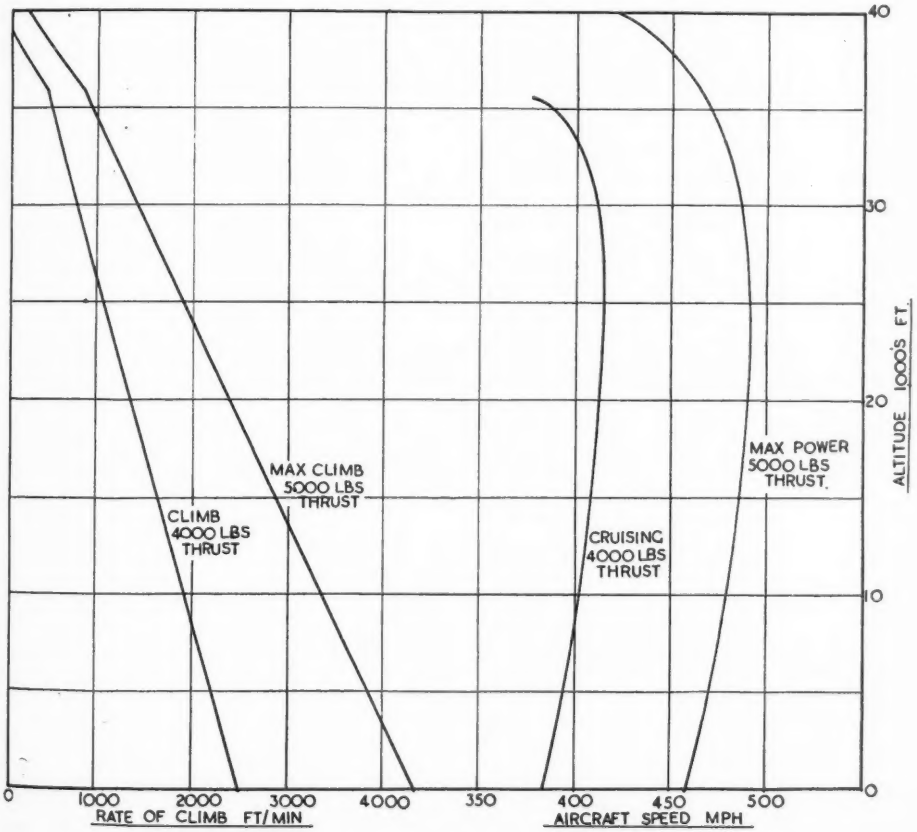


Fig. 21
Lancaster Performance with 4 Nene Engines.

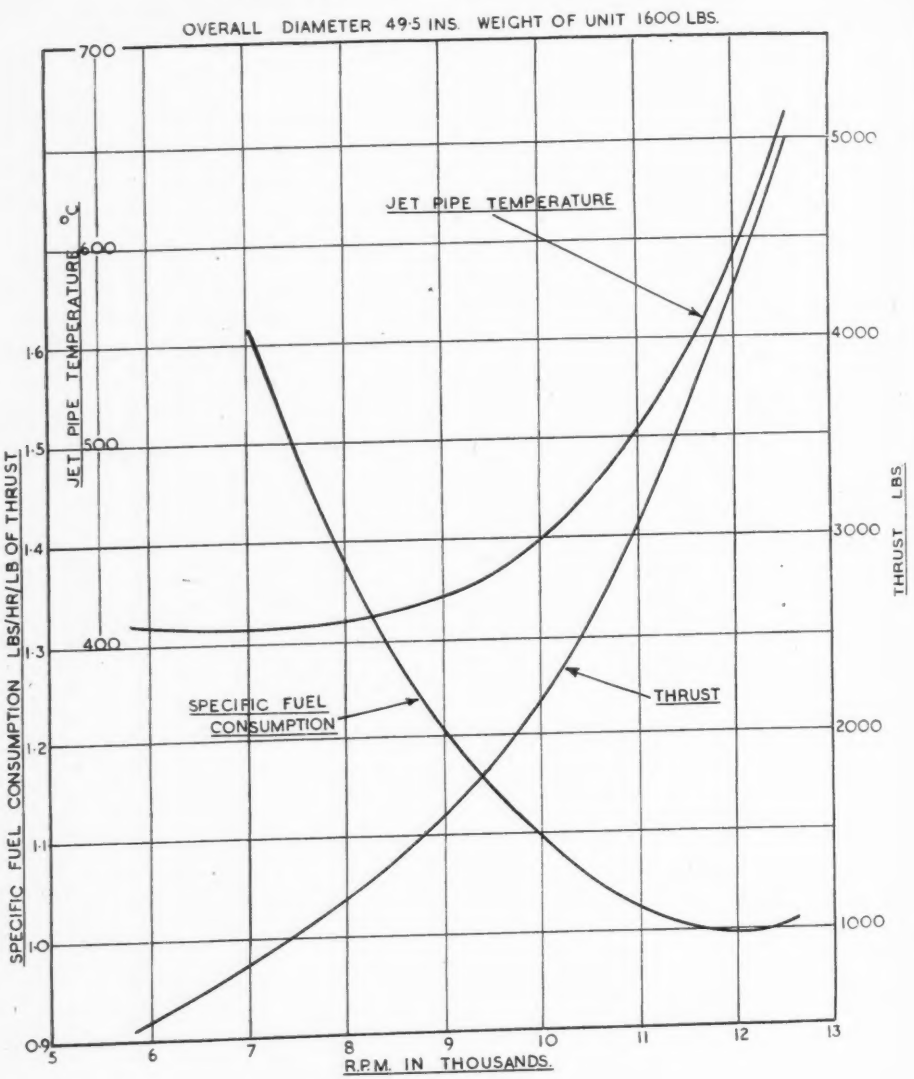


Fig. 22
Rolls-Royce Nene Engine Test Bed Performance.

heat exchanger, the thermal efficiency of the cycle becomes independent of the r.p.m. of the engine over quite a wide range of conditions, which is a very important feature from the point of an aero engine.

Obviously, a heat exchanger has very little effect upon the power produced by the engine, provided that it is well designed so that the pressure losses on the hot and cold sides are small. This condition will be found to make the heat exchanger rather heavy and bulky and consequently, this additional engine weight will only be saved in terms of fuel if the range of the aircraft

is sufficiently great. Calculations indicate that somewhat more than 5 hours flying must be done before a heat exchanger has paid for its own weight.

In addition, the mechanical problems to be faced in the development of an efficient, reliable, and low pressure loss heat exchanger, are very great. It is the radiator problem—*in excelsis*!

9. PERFORMANCE OF JET-PROPELLED AIRCRAFT.

Having eliminated pistons and reciprocating motion with gas turbine engines, the next component that we should all like to see die an honourable death, is the propeller. If we really must crawl about the skies at 200 m.p.h., then I see no hope for displacing the propeller, and as a punishment we shall have to put up with the propeller noise and vibration. If, on the other hand, we regard a journey by air as a boring thing to be got over as soon as possible, and are prepared to consider transport aircraft with cruising speeds greater than 400 m.p.h., then we can begin to think of the jet propulsion unit with the advantage of its reduced noise and vibration for the passengers. Speed is always expensive in fuel, no matter how it is obtained, so that in our high speed jet propelled machine, we must be prepared to revise our ideas on fuel consumed. Fig. 21 shows the performance of a Lancaster fitted with four Nene engines. You will note that at cruising thrust, the aeroplane has a cruising speed of about 400 m.p.h. at all altitudes up to 35,000 ft.

At 10,000 ft. each engine will consume about 430 gallons per hour, so that the air miles per gallon are 0.23. At 20,000 ft. the corresponding figure is .31 air miles per gallon, and at 30,000 ft. .43 air miles per gallon. Admittedly, these are low figures, but it should be remembered that four jet propelled units of this type will only weigh, when fully installed, a total of about 7,000 lb., whereas the present four Merlins fully installed weigh 13,000 lb. In addition to this, the remainder of the airscrew slipstream over the wings will appreciably reduce the drag of the Lancaster, no allowance for which has been made in the above calculations.

Pursuing this latter point, a jet fighter aircraft such as the Meteor, Vampire and Lockheed Shooting Star, have drag figures very much lower than airscrew-driven machines of similar size, e.g., the drag co-efficient of the Meteor is only about two-thirds of that of the Spitfire, and figures for the Vampire are even better. Consequently, as a conservative estimate, I think that the previous figures of air miles per gallon can, in actual fact, be increased by about 25 per cent. In addition to this, jet engines with a fuel consumption of some 14 per cent less than that of the Nene can be designed and made, as indicated earlier in my lecture.

So far as take-off is concerned, it will be noted that the Lancaster fitted with four Nene engines will have a static take-off thrust of 20,000 lb. which is considerably greater than from four Merlin engines, even after every form of liquid known to man has been injected into the engine.

It is improbable that the Lancaster would be able to fly the Atlantic direct to New York. But I respectfully suggest that it will have little difficulty in crossing the English Channel, and reaching very attractive places like Paris, Stockholm, Copenhagen and Zurich!

On these comparatively short ranges, the speed is not so important, since the time of the journey will be more affected by the dead time at the customs, and airports. On the other hand, I suggest that the comfort and smoothness of this form of travel will be unsurpassed either on land, sea or air.

Let us consider another case, namely the celebrated DC-3 replacement aircraft. Fig. 22 shows approximate details of such a machine.

With a cruising speed of 400 m.p.h. at 1,000 ft. and 5,000 lb. pay-load, a range of

1,000 miles can be obtained at a take-off weight of 27,000 lb. using jet propulsion engines of about 6 : 1 compression ratio and a static thrust of 6,000 lb.

10. THE EFFECT OF ALTITUDE UPON RANGE.

The preceding figures for the Lancaster indicate the important effect that altitude has upon the range of jet propelled machines. Fig. 23 analyses its effect in more detail. The calculations are based on a machine of about Spitfire size, which has a drag of about 1,000 lb. at 300 m.p.h. at sea level. For a sea level speed of 500 m.p.h. a thrust of 2,400 lb. will be required, and the air miles/gallon of the machine will be reduced to about 1.0. At 40,000 ft. the drag of the aircraft at the same speed of 500 m.p.h. will be reduced to about 800 lb. due to the lower density of the air at 40,000 ft., and also the change in angle of incidence of the machine. Consequently, at this altitude the air miles/gallon will be about 4.0. On the right hand side of the figure, you will note that in going from sea

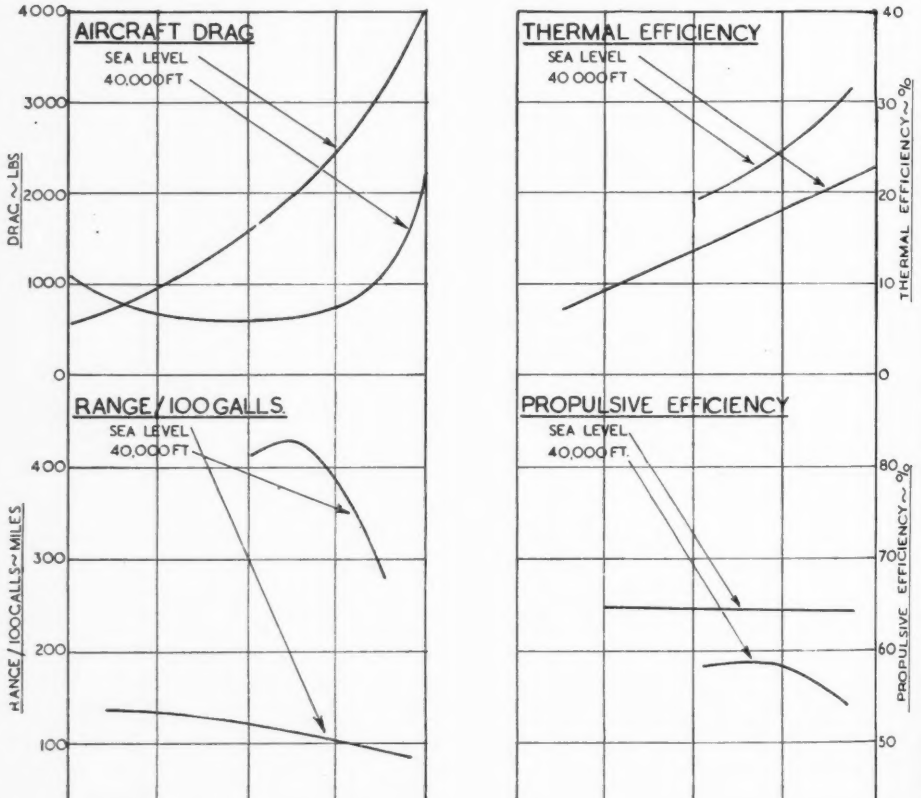


Fig. 23
Fighter Aircraft. Analysis of Factors Governing Range.

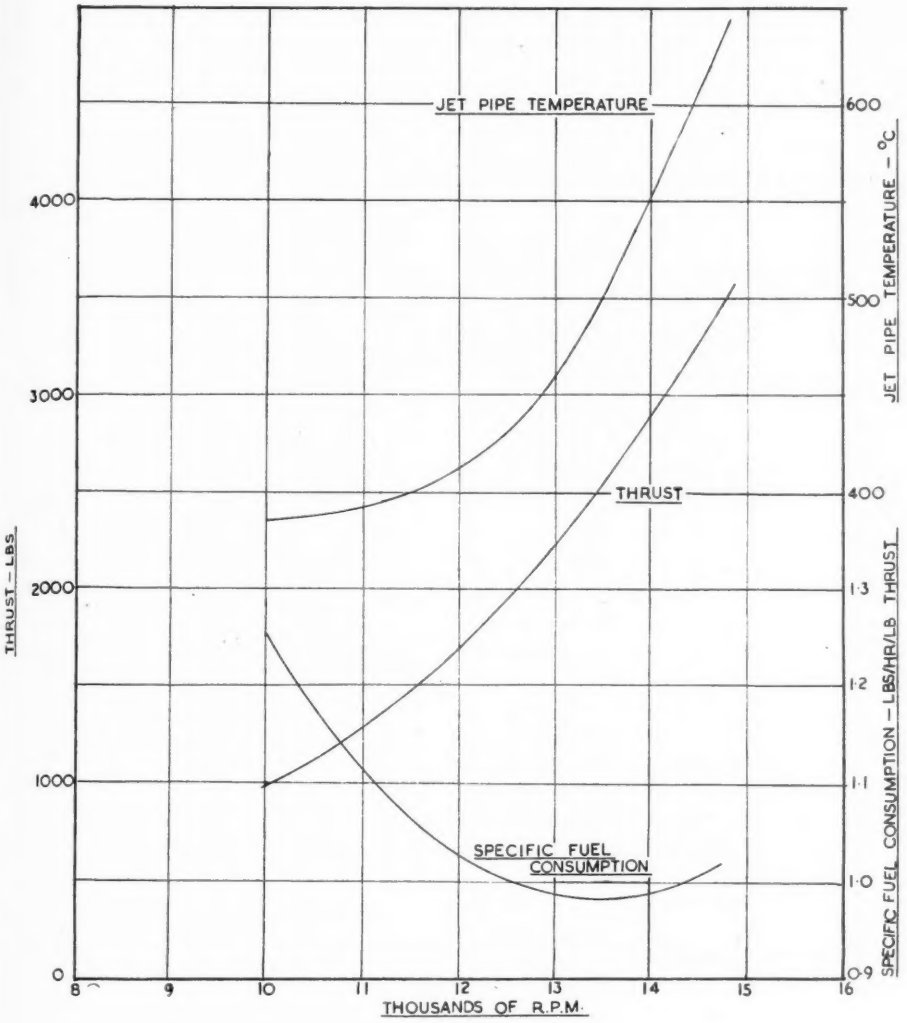


Fig. 24
Rolls-Royce Derwent Series V
Static Performance at Sea Level.
Overall diameter 43.5 in. Weight of Unit 1,260 lb.

level to 40,000 ft. the thermal efficiency of the engine is improved from about 18 to 25 per cent. This improvement is due to the lower air intake temperature to the engine, and the consequent high compression ratio of the cycle. On the other hand, the propulsory efficiency of the jet has fallen from 64 to 58 per cent due to the increased jet velocity at 40,000 ft. because of the increased thermal efficiency of the engine. Thus, the balance is as follows:—

Improvement in thermal efficiency of engine from 18 to 25 per cent, i.e., 1.39.

Reduction in propulsion efficiency from 64 to 58 per cent, i.e, 0.90

The overall improvement of the engine is,

therefore, 25 per cent., whereas the range of the aircraft has actually been quadrupled. Hence, the improvement in range of a jet propelled machine at altitude is not so much due to the engine, but in the main, due to the aircraft.

In actual fact, you will note that at 40,000 ft. and 500 m.p.h. this machine does the same air miles/gallon as a Spitfire, and consequently, all the objections to jet propulsion can be overcome by flying high and fast. It should be clearly understood that jet propulsion is efficient at any altitude, provided the speed is greater than 500 m.p.h. It should also be remembered that the higher the altitude, the more efficient the aeroplane.

Fig. 24 shows a comparison of performance of piston and jet engines at high altitudes.

I have taken the case of a jet and reciprocating engine of equal power at 35,000 ft. The speed, for comparison purposes, is estimated to be 300 m.p.h., in both cases, so that lb. of thrust and b.h.p. are mutually interchangeable. Due to the greater mechanical loss in the reciprocating engine, the power of this engine will fall off at a greater rate than the power of the jet engine, and at 50,000 ft. the jet engine gives something like 20 per cent more power than the reciprocating engine. In other words, the requirement that the jet propelled machine must fly high and fast, is somewhat helped along by the fact that the jet engine is the most suitable type for high altitude work.

11. FINAL CONCLUSIONS.

The advent of the gas turbine has provided us with a power plant incomparably lighter than the conventional reciprocating engine. In addition to this, the mechanics of the engine allow us to operate it continuously for cruising conditions at a much higher proportion of its maximum power than is possible with the piston engine. To utilise these advantages in the best manner, we must operate our aircraft at higher altitudes where the resistance to motion at a given true air speed is reduced because of the reduction in the air density. Thus, the necessity for pressure cabins becomes more urgent, and every possible effort in this country should be made in the development of a satisfactory pressure cabin.

With these light and high powered units flight at high altitudes and high cruising speeds can be envisaged, and as the speed of the aircraft increases, so jet propulsion becomes the most desirable and efficient means of propelling the aircraft. Jet propulsion units give far less noise and vibration to the aircraft structure and thus contribute towards the comfort of passsenger travel.

The installation of a jet engine is very much simpler than that of a piston engine and because of the simplicity of the jet unit its liability to mechanical or functional failure must and will be reduced. For the same reasons the maintenance required by jet units is very much less than that of conventional engines. This reduction in maintenance and the high cruising speeds will be reflected in the serviceability and the flying hours of the aircraft, and I venture to suggest will materially affect the cost of maintaining an air service. Safer and cheaper fuels can be used with gas turbine engines, and the danger of an uncontrollable fire is appreciably diminished.

Engines can be grouped closely together and installed close to the fuselage of the machine. In this way, the risks at take-off, if one engine should cut, are considerably diminished.

There are other advantages which, no doubt, will be put in a more powerful manner by subsequent lecturers. For my part, I have tried to lead the horses to the water. It only remains for them to drink before the drought sets in!

TURBINE COMPOUNDING OF THE PISTON AERO ENGINE

by

Dr. H. R. RICARDO, F.R.S., Fellow

I HAVE been invited to-day to put forward the case for the compounding of a piston engine with a turbine, and this I propose to do in very general terms.

This is a scheme which we investigated fairly fully, both theoretically and experimentally, some ten years ago, and with which we would have proceeded actively had not the war, and consequent pressure on more immediate problems compelled us, temporarily, to lay it aside. It is only during recent months that we have been able to return to the attack, in terms of actual hardware. In the meantime, intensive development of both the turbine and its blower has rendered the compound unit far more attractive, for we now have available well proved and reliable ironmongery to take care of the low pressure end of the cycle.

I think we are all agreed that, where very high speeds are called for, the simple turbine reigns supreme and, by the simple turbine, I mean the low pressure form in general use to-day, the product of that brilliant pioneer, Air Commodore Whittle. By virtue of its very low power/weight and power/bulk ratios, this form of prime mover is almost ideal for very high speed machines or for flight at very high altitudes.

Compared with the conventional piston engine, it has, apart from its low weight and bulk, the advantages of simplicity, freedom from vibration and freedom from cooling problems, while its very high mechanical efficiency and its love of cold, give it increased vigour the higher it goes.

It is, unfortunately, very greedy of fuel. There are, however, on the drawing board or in process of development, more complex forms of turbines for long-range aircraft, which will be more economical in fuel, though at a considerable cost in weight or bulk.

It is with these more complex forms of turbine, rather than with the simple types of the present day, that the compound engine will have to compete.

I do not propose to-day to go into the thermo-dynamics of the turbine or the piston engine, except in very brief and general terms. Clearly the efficiency of any heat engine is a function of the range of temperature it can usefully employ. The turbine is handicapped by the fact that the upper limit of the temperature range through which it can work, is to-day in the region of 700°C, while the flame temperature attained by the combustion of any hydro-carbon fuel in air, lies between the limits 2,200°C. and 2,500°C. and is nearer the upper limit if the flame is to be kept as short as possible. To bridge this wide gap between the maximum temperature available and that which we dare to use, a very large amount, some four or five times that of the combustion air, must be supplied as a temperature dilutent. If this air were a free issue it would not matter, but it has all to be supplied, under pressure, by a blower whose efficiency is considerably less than 100 per cent. Future developments in the way of improved materials or blade cooling will, no doubt, permit of higher temperatures being employed, but it is hardly conceivable that they will go far

enough to permit of any very large reduction in the proportion of dilution air required.

The conventional piston engine, on the other hand, can utilise to advantage the upper ranges of temperature, but can make little use of temperatures much below about 1,500°C. We have, therefore, two forms of prime mover, the one eminently suitable for converting into power the heat available in the higher temperature ranges, the other for conversion of the low temperature heat, and that without any overlapping; rather, there is still a considerable gap between the minimum temperature of which the piston engine can make efficient use and the maximum which the turbine can digest.

Again, the piston engine is eminently suitable to deal with relatively small volumes at high pressure and temperature, and the turbine, by virtue of its high mechanical efficiency and large flow areas, to deal with large volumes at low pressures. Clearly then, the logical development is to combine the two, in series, to form a compound unit. Instead of lowering the temperature by pumping large volumes of dilution air, at a heavy cost in blower work, let us lower it rather by converting the high temperature heat into useful power; in other words, let us interpose between the blower and the turbine, a dynamic rather than a static combustion chamber. By so doing, we can hope to reach an overall efficiency far in advance of that attainable by either element alone.

The usual and the obvious objection to such a compound plant is that it combines the complexities of both types of prime mover and must necessarily be very heavy as compared with the straight turbine.

I am going to argue that, by virtue of certain favourable circumstances, the complexity can be minimised, while the added weight and bulk will be little, if any, greater than that which we shall have to add to the simple turbine, if we are going to render it even two-thirds as efficient as the compound unit.

In the piston engine, both weight and bulk are a direct function of the total cylinder capacity. In order to keep the cylinder capacity as small as possible, our first consideration is to get the utmost possible energy out of every pound of air inhaled by the cylinders. We have, therefore, to achieve the highest possible thermal efficiency in terms not only of the fuel, but also of the air consumed, and it is in order to comply with this latter condition that much of our present complexity is due. In the combined plant, we shall have available a considerable excess of air over and above that required for complete combustion, for, as I have said earlier, there is still a gap between the minimum temperature of the piston engine cycle and that which the turbine can digest. In the present state of the turbine art, the gap is such that we shall have to provide nearly two and a half times the air required for complete combustion of the fuel, so we need not worry about thermal efficiency in terms of air consumed nor, so far as the piston engine is concerned, need we worry over-much about efficiency in terms of fuel, for what is lost in the cylinder by delayed or incomplete combustion, will be recovered in the turbine; the only irrecoverable loss will be that of direct heat to the cylinder walls. We must, therefore, revise entirely our ideas as to piston engine design. Our objective is now to develop an engine which shall offer the freest possible passage of air through its cylinder and which shall be capable of burning the maximum possible amount of fuel per unit of cylinder volume.

In the first place, thanks to the excess air, we can employ a two-stroke engine, and therefore a much smaller cylinder, since a two-stroke engine can pass far more air than its cylinder volume defines. Again, and for the same reason, we need not worry about scavenging efficiency and can use the

simplest possible expression of two-stroke with piston controlled ports, as used in the ordinary lawn mower engine; thus we shall be saved all the complexity of valves and valve-operating mechanism.

Yet again, in view of the fact that we cannot, in any case, burn all of the air available, we can, with advantage, employ compression ignition in preference to spark ignition, since the over-riding objection to compression ignition as applied to the conventional type of aero-engine, namely its poor efficiency in terms of air consumption, no longer applies, for in the compression ignition engine, as in the turbine, we are compelled to provide some surplus air; not in this case as a temperature dilutent, but rather because we cannot, for practical reasons, search out and combine the whole of the air entrapped in the cylinder. The use of compression ignition, in this connection, confers additional advantages:—

(1) We need not worry about maintaining any sort of relationship between the fuel and air; hence the control can be on the fuel supply alone, as is the case with the simple turbine.

(2) We are completely exempt from the menace of detonation and need not, on that score, intercool between the blower and the engine; on the contrary, the hotter the air, within the limits imposed by lubrication, the better the combustion and the smoother the running of the engine. Neither is our ratio of compression or expansion in the engine cylinder limited by the incidence of detonation, or pre-ignition due to high intake temperatures.

(3) Its taste in fuels will be the same as that of the straight turbine and we shall need neither high octane nor any very volatile or low flash-point fuel.

(4) We shall be free of electrical ignition with all that that implies in the way of weight, wireless interference, and potential sources of failure.

The actual size of our piston engine will be very small; it will be determined almost solely by the amount of fuel we can burn, under take-off conditions, per litre of cylinder capacity per hour, and this, in turn, will depend largely upon the pressure at which we choose to operate our turbine. The higher the pressure, the greater the weight of air entrapped in our cylinder, and therefore the more fuel we can burn in any given size of cylinder. On the other hand, the higher the turbine or blower pressure, the lower the compression ratio we can employ in the cylinder itself, if we are to keep our maximum cylinder pressure within bounds and, at the same time, operate on something approaching a constant volume cycle. Again, the lower the compression ratio in the engine cylinder, the higher will be the temperature of discharge, and therefore the more dilution air we shall require for the turbine's sake.

Taking all these factors into consideration, it would seem that the best all-round compromise will be to work at a pressure of round about 6 atmospheres absolute for maximum power; it will be found, however, that the overall efficiency will vary very little over a wide range of pressure; for what we lose on the swings, we gain on the roundabouts. Generally speaking, the higher the pressure at which we operate, the more we shall throw the burden of power production on to the turbine and the smaller the size and output of the piston engine.

With the component efficiencies which we realise to-day and taking fully into account the losses due to direct heat flow to the cylinder walls and to pressure drop through the engine cylinders, the overall efficiency from the fuel to the airscrew shaft of such a compound plant should lie between 40% and 45% when cruising at 15,000 feet at 50% of the take-off power, corresponding to a consumption of Diesel oil of 0.3 to 0.34 lb. per shaft horse-power hour, rising

to about 0.4 lb. under take-off conditions.

These figures take no account of the additional jet thrust available. I am deliberately avoiding taking this into account since its value depends so largely upon the speed and altitude at which the machine is operating. It must be remembered that it will be there at all times, as a bonus, and under some conditions, as a really substantial bonus. The specific consumption, in terms of airscrew shaft power, will vary very little with altitude, for while the performance of the turbine will improve, that of the piston engine, owing to its lower mechanical efficiency, will tend to diminish with altitude. Since, however, the turbine is the dominant partner, there should be a net overall gain with altitude.

We come now to this conclusion; the combined plant will consist of a blower, preferably, I think, an axial flow blower, with perhaps a centrifugal for the last stage, a very small, and I want to emphasise that it may be a very small and very simple, piston engine in place of the usual combustion chamber, and a gas turbine. Of these three components, the piston engine will deliver, and the blower will consume, about the same power, while the turbine will deliver about 50% more than either. Since the power output and power consumption of the piston engine and blower will be substantially the same, it would appear logical that these two should be coupled together, leaving the turbine free to provide all the take-off power.

On the other hand, since both the turbine and the blower run at about the same speed, it would also seem logical to couple these together and so save some gearing. In that case, the power take-off would be, in part, from the piston engine and, in part, from the turbine, the surplus of which could either be transmitted back to the engine crankshaft or used to drive a separate airscrew. This, however, does not appeal to me as a very satisfactory arrangement, nor does it provide any means for aspirating the engine before the turbine has got under weigh. A better alternative, I think, would be to drive the last or centrifugal stage of the blower from the engine crankshaft and the rest of the turbine, in which case the surplus power available from engine and turbine will be about the same. The latter could then either be geared together or used to drive separate airscrews.

I referred earlier to more complex forms of turbine which are in sight and for which there are great expectations. It goes without saying that anything the designer or metallurgist can do to raise the working temperature of the turbine will be all to the good, for it will both extend the useful temperature range and reduce the present very high ratio of dilution to combustion air; but the scope in this direction is probably very limited. In any case, any improvement in this direction will help the compound unit also.

If we are going to improve really substantially the efficiency of the straight gas turbine, we must adopt one or other of two courses; either we must work with a very high overall pressure ratio, something in the neighbourhood of 16 or 20, or stick to our present low ratio and conserve fuel by using waste in place of live heat; in other words, by using a heat exchanger.

Either course will yield a substantial gain and it is debatable which is to be preferred. Either course will involve a great increase in bulk, or weight, or both. If we go for a very high compression ratio, then we must face the fact that the high pressure stages of the blower, the combustion chambers, ducting and turbine casing, will all be subjected to a pressure of nearly 300 lb. per square inch, and that at temperatures ranging from 300°C to 700°C or even higher. Anyone with experience of high pressure, highly superheated steam, will know what problems this involves in the way of jointing,

expansion troubles, and so on. Further, the temperature of the blower rotor and casing will probably be too high to permit of the use of light alloys. I am not suggesting that these problems are likely to prove insuperable, but I am suggesting that their practical solution will be achieved only at the cost of a very considerable addition of weight, much greater, I fancy, than most people realise.

The other general line of approach is to work with quite a low compression ratio and swap exhaust heat for live heat. This entails the use of some form of heat exchanger. While clearly there is scope for much ingenuity in the development of such a heat exchanger, yet it is evident, I think, that it must necessarily be very bulky. Consider the problem; we have to swap heat from something like a ton of air per minute with an extreme temperature difference of only about 400°C. and that, too, without any appreciable back pressure. Some form of rotary heat exchanger would seem the most promising line of approach, but, even so, it is difficult to see how it can be anything but very bulky and it will bristle with problems in the way of thermal expansion, gas tightness, etc., while, to be even reasonably efficient, it will have to be made up of multitudes of very narrow passages which must be kept free from clogging with carbon or other deposits. Again, I am not suggesting that the problem will prove insuperable, but I do contend that its practical solution will involve a very great increase in the bulk of the simple turbine plant.

To sum up then; apart from raising the working temperature of the turbine, which is a purely mechanical and metallurgical problem, there would appear to be two possible lines of approach whereby the present low efficiency of the gas turbine may be improved; by the use of a high working pressure or by the use of a really efficient heat exchanger. Either method offers the possibility of bringing the specific fuel consumption down to somewhere between 0.4 and 0.5 lb. per shaft horse power hour. The former must involve a great increase in weight but not much in bulk; the latter a great increase in bulk but not so much in weight.

Turning now to the compound unit; it is generally argued that the addition of a piston engine will involve a very great, if not a prohibitive, increase in both weight and bulk. I am very doubtful whether it will add as much weight as will be entailed by raising the working pressure of the straight turbine, or as much bulk as the addition of a heat exchanger.

I said earlier on, that the piston engine may be very small and very simple; let us consider this more closely. The actual capacity of the engine is determined by the amount of fuel which can be burned per hour per litre of cylinder capacity. Our preliminary experiments with a simple valveless two-stroke cylinder working with an inlet pressure, so far, of only 4.4 atmospheres absolute, at 2,800 r.p.m., show already that we can burn between 50 and 60 lb. of Diesel oil per hour per litre of cylinder capacity, with a maximum cylinder pressure not exceeding 1,400 lb. per square inch, and without running into any thermal troubles, such as overheated pistons, stuck rings, etc. I am hopeful that when, as we intend, we go up to a pressure of six atmospheres and higher revolutions, we shall be able to increase this figure to about 80 lb. but to be on the safe side, let us assume that the weight of fuel burnt will be 64 lb. per litre per hour, under take-off conditions. If now the overall specific consumption, under take-off conditions, is 0.4 lb. per b.h.p. hour, then the net power output of the complete plant will be 160 horse power per litre of piston engine.

Now as to weight. The current weight of aero-engines, working at similar maximum pressures, when stripped of their

superchargers, their ignition equipment, and such auxiliaries as will form part of the turbine plant in any case, works out at between 40 and 45 lb. per litre. A valveless engine should be considerably lighter, but let us take the weight as 40 lb. per litre. The weight, then, of the piston engine in the combined plant should work out at about 0.25 lb. per shaft horse-power. By no means all this weight is additional, for it must be remembered that the engine replaces the combustion chambers; further, since the mass flow of air will be approximately halved, the blower, the turbine and all the ducting will be correspondingly smaller and lighter. Moreover, nowhere, except inside the engine cylinder, will the pressure exceed, say, six atmospheres absolute. This figure for weight may sound optimistic, but we must remember the very small size of piston engine required. As an illustration, an engine of the same cylinder capacity as the old Bristol Mercury should suffice for a net output of 4,000 shaft horse power.

In view of the large excess of air available, I am in favour of using a simple single piston valveless engine of what is generally termed the "loop scavenged" type. This is the simplest possible expression of a piston engine and the lightest in terms of weight to cylinder volume ratio. It has moreover, the advantage of greater port area and therefore less pressure drop than any form employing valves. So long as the limitations of the turbine compel us to employ something like two and a half times as much air as we need for combustion, we need not worry about its relatively poor scavenging efficiency, for we can afford to give the cylinder a thorough blow through at every cycle. If design or metallurgical improvements in the future permit of the turbine being operated at a higher temperature, so much the better for the compound unit also, for we shall save considerably, both in blower work and by reduced pressure drop through the cylinder, though the latter can always be reduced by allowing any surplus air to by-pass the cylinder merely by a direct leak from inlet to exhaust. If they permit of much higher temperatures so that the total air available is substantially less than double that required for complete combustion, then we may have to resort to some more efficient form of two-stroke engine, efficient, that is to say, from the point of view of scavenging and therefore of air consumption. The choice will then lie, I think, between the opposed piston valveless or the single piston sleeve-valve type, both with end to end scavenging.

I have ruled out the four-cycle engine, because the four-cycle cylinder is normally a cul-de-sac, and can pass no more air than its volume defines; nor is it possible to burn anything like so much fuel in a given size of cylinder; hence, a four-cycle engine would have to be very much larger and, of course, far more complex. I do not, however, want to ignore this possibility entirely, for there are some arguments in its favour.

With a two-cycle engine, as with the straight turbine, the blower pressure must always be in excess of that available to the turbine, by an amount depending on the pressure drop through the cylinder or combustion chambers; whereas, with the four-cycle this can be reversed, for the four-stroke piston engine can be used to step up the pressure, but in that case, either the cylinders will have to be large enough to displace the whole of the air delivered, or an additional blower stage will have to be added to step up the by-passed air; neither of which alternatives appeal to me as attractive. Yet again, either by using a very large valve overlap or by by-passing, the four-cycle could pass more air than its volume defines, but this would be merely imitating the two-stroke, without achieving its simplicity.

The strongest objection to the use of the four-stroke cycle rests in the amount of fuel

which can be burnt in a given size of cylinder; this is only about half of what is possible in a two-stroke and it is, I think, an overwhelming objection so far as its application to aircraft is concerned.

I have not, so far, referred to the free piston version. This is another alternative form of two-stroke but, frankly, I, personally, do not like it much. I may be prejudiced, but I do not like pistons and automatic valves to deal with very large volumes of air at relatively low pressures.

I am not so afraid of a crankshaft that I would be prepared to forego the advantages of rotary motion both for my blower and for my engine auxiliaries, and I do like to know, for certain, just how far my pistons are going at each cycle.

DISCUSSION

AIR COMMODORE F. R. BANKS (D.E.R.D., M.O.S., Fellow): He was a supporter of the gas turbine, but because the active development of the jet propulsion turbine had shown startling results over relatively few years, people were apt to run away with the idea that there was nothing more to do than fit these engines in a transport aircraft and career about the world at will. This picture was misleading because, although they had proved that the jet propulsion turbine could take the place of the piston engine in military aircraft, particularly fighters, the ordinary public were apt to generalise and to forget that there were propeller as well as jet propulsion turbines and did not realise that the propeller turbine was probably going to take as long to develop as some of the later piston engines. It would be at least three to five years before a practical and safe passenger transport aircraft could be operating *on the routes* with this jet propulsion turbine.

The development of the gas turbine needed no apologia, since high output jet propulsion turbines could be developed and produced in about a third to a quarter of the time of the piston engine of equal power. Dr. Hooker's firm had demonstrated this beyond all question of doubt during the past three years or so. It was for this reason that he deplored the tendency to " over sell " the gas turbine when its progress had been so promising and had exceeded all expectations.

In his position he must be dispassionate and hold a balance between over-optimism and practical attainment. The author had given a total development time for the Derwent V engine of three months ! He felt it was misleading because gas turbines lent themselves much more easily to scaling up or down than piston engines. The Derwent V was merely another Mark of the Derwent series, although it gave a much superior performance.

When they came to a different type, such as the turbine with an axial flow compressor and departed from the original Whittle design, then the development time started to lengthen because of the basic difference between the compressors and because, fundamentally, an axial flow compressor would appear to take a longer time to design than a centrifugal one. Propeller turbines were going to take longer still to design and develop; certainly until more experience with them had been obtained.

He mentioned the question of " Dutch auctions " in thrust, but subsequently stated that he had used this term in the wrong sense and meant that firms, far from giving less thrust than they had promised, had given increased thrust in large amounts in the early development stages of the engines. But that was sometimes very embarrassing, particularly when reliability suffered; as it often did.

He felt that Dr. Hooker, in his comparisons of propeller efficiency, had been too conservative and on the latest information they had, a propulsive efficiency of 75 per

cent. was now thought quite possible at 550 m.p.h.

The gas turbine was quite vulnerable to battle damage in the case of military aircraft and, even for civil transport purposes, would have to be installed with great care and with the same degree of protection against fire hazard as was necessary now for pistoned engines.

On the question of pure jet propulsion, which, he presumed, was the ultimate aim, it would be a good idea if one engine firm, together with one, or two, aircraft firms, were told that they would never see a propeller again and they must concentrate only upon jet turbine type aircraft. They might then have practical transport aircraft of high speed more quickly and learn how to handle them, both in the air and also from the point of view of control over the aerodrome.

He did not think that heat exchangers would be the final answer for aircraft gas turbines of high economy, but, rather, turbines of the double compound type with high pressure ratios would be used in preference.

There had been very satisfactory developments with materials for turbine blades and discs but he felt that they could not expect further big advances in heat resisting materials except over long periods of time. The turbine manufacturers should concentrate seriously upon the cooling of the turbine wheel and blading. By this means one could foresee a turbine with the existing materials being able to operate at gas temperatures some 200°C. greater than at present allowed. In any case, most of the present materials would fade out at 1,400°C. and it might be necessary to provide blades with ceramic covering, in addition to cooling them.

Dealing with the question of the basic simplicity of the present type Whittle gas turbine, he said that, while simplicity was obviously the thing to aim for, it had rarely been retained in aviation where improvement in performance was always accepted, even at the cost of some complication.

Dealing with Dr. Ricardo's paper, he agreed that there was a case for the compound engine of the two-stroke turbine type. There was no doubt that the size of long-range aircraft was seriously influenced by the fuel consumption of the engine. For instance, an aircraft requirement was recently considered by the Ministry where endurance was of principal importance and was equivalent to 7,500 miles range. It was found that the difference between a cruising fuel consumption of 0.45 lb. b.h.p./hour and one of 0.35 lb./b.h.p./hour was something in the order of 60,000 lb. in the all-up weight of the machine; two quite different aircraft, in fact.

In regard to the free piston engine, he said that, like Dr. Ricardo, he wanted to know where the pistons were going. It had taken long years of development to obtain satisfactory connected pistons without having to worry about free ones !

MR. O. N. LAWRENCE (Joseph Lucas, Ltd., Associate Fellow). He was puzzled by a statement in Dr. Ricardo's paper that the blower pressure at the inlet to the engine must always be higher than at the exit to the turbine. Surely that referred to the mean pressure ? It was fundamental to an engine working on the constant volume cycle that the gases, at the instant the exhaust port opened, were at a pressure nearly double that of the entry air. That factor could not be influenced in the case of the engine Dr. Ricardo had mentioned, by the timing of the valves, *i.e.*, by having a shorter compression stroke compared with the expansion stroke. Naturally, scavenging must be undertaken, and during that part of the cycle the exhaust pressure must be below the inlet pressure.

Probably Dr. Ricardo had assumed that

the high exhaust pressure was dissipated in turbulence in coming out of the exhaust port and could not, therefore, be used in the turbine. Were it possible to make use of that pressure, the thermal cycle would be that known as the Atkinson, and a gain of some 12 per cent. in thermal efficiency, *i.e.*, about 15 per cent. in engine fuel consumption, would result.

Buchi, in his turbo supercharging of 4-cycle Diesel engines, had found it necessary to use two separate exhaust pipes and a special sequence of cylinder firing to overcome the interference between the exhausts of different cylinders. Did Dr. Ricardo think that any such special measures would be necessary on his engine, or how would he prevent one quantity of high pressure exhaust interfering with the scavenging of other cylinders? On 2-cycle engines the times of valve opening were, comparatively, so much shorter that that difficulty might not arise.

MR. H. PEARSON (Rolls-Royce, Ltd.): He had listened to the two papers with absolute amazement. The first lecturer told them that the great advance that Whittle had made was to put down the engine weight by about ten-fold and increase fuel consumption; the second paper had shown that the next thing to do was to put the engine weight back again and to reduce the fuel consumption.

There could be only one test, namely, how did the aeroplane like it? Presumably the other lecturers this afternoon would deal with this, but anticipating them, it seemed that there must be a limited application of both types. He suggested that the application of the compound engine would be limited, and that it would be applicable only to the very long-range aircraft. The amount of use to which they could put it was so limited that they might be throwing away a great deal of effort for a very small return; and in view of the limited resources in this country, that effort could not be afforded.

MR. R. H. P. NOTT (Miles Aircraft, Student): The large gas turbine seemed to have made such advances in a short space of time that, not only in the field of aviation, but in many other fields, it seemed to have become a firmly established prime mover. Even where solid fuel was to be burned, the promising results already achieved with the closed cycle "aerodynamic" turbine of Escher-Wyss made it likely that this machine would soon become a serious competitor to orthodox steam turbine plant. Should it become possible to make gas turbines in much smaller sizes, it seemed that they would have something approximating to a universal prime mover.

Could Dr. Hooker give any information about the efficiencies of very small blowers and very small turbines? He understood that on a unit of 100 b.h.p., in order to achieve a thermal efficiency of 25—30 per cent., for which a relatively very large heat exchanger would be required, it would still be necessary to achieve a turbine efficiency (total to total) of about 90 per cent. It would be interesting to know whether figures were available on such small wheels as would be required for a 100 h.p. unit. He understood they would be only of 4—5 in. mean diameter.

The only small gas turbine unit of which he had knowledge was the Westinghouse. The thrust h.p. was in the region of 300, the turbine speed was about 34,000 r.p.m., and the overall diameter of the unit about 9 in. Had Dr. Hooker any information on turbine efficiencies and compressor efficiencies?

Experimental work had been done on very small axial flow wheels, notably at Göttingen, in which stage efficiencies up to 92 per cent. had been achieved; the wheels being only of about 6 in. diameter. It would be interesting to know over what range those

exceptionally high efficiencies could be achieved on such small wheels.

THE REPLIES.

DR. HOOKER:—

Air Commodore Banks. There were few points on which he agreed with Air Commodore Banks. Many years were occupied in building a civil transport; if they started to build a machine now, there was no question that the jet propulsion units for it could be developed to a state of reliability far greater than had yet been reached by any piston engine. One of the great difficulties was the vicious circle around which they travelled; jet engines and aircraft were not fully developed; therefore, they must continue with the development of piston engines and aircraft, and hence, there were not the facilities to develop the jet engines, since these were all absorbed developing piston engines and the aircraft for them.

The claims for the reliability of the jet engine were fully justified; the first Derwent V engine, built from the drawing board, had run for 100 hours continuously. That was something which no other aero-engine had ever done. Did Air Commodore Banks deny that they had gained the World's speed record with the jet engine? The first line of that engine was not drawn until January 1st, 1945, and the record was taken in October of the same year.

The Whittle engine was designed for 1,600 lb. thrust, and actually gave 1,700 lb. thrust. The Derwent Mark I was designed for 2,000 lb. thrust, and had given 2,000 lb. in service. The Goblin was designed for 3,000 lb. thrust and would give that, and more, in service with reliability. The B.41 was designed for 4,000 lb. thrust, and had done 100 hours continuously at the rated power.

His curve for airscrew efficiencies was 12 months old, and perhaps was unduly pessimistic. In his calculations he had always taken an efficiency of 80 per cent. at 400 m.p.h. and 53 per cent. at 600 m.p.h. and the curve between those two points was continuous. He agreed that efficiencies greater than 70 per cent. at more than 500 m.p.h. might be obtained, but only at the expense of complexity and weight of the airscrews.

Mr. R. H. P. Nott. He had no definite information with regard to the efficiencies of very small axial compressors and very small turbine wheels. The Westinghouse unit referred to, which was 9½ in. in overall diameter, did not have a particularly good thermal efficiency, but whether this was due to the turbine or to the compressor he did not know.

He saw little difficulty in building quite small capacity centrifugal compressors with efficiencies equal to the larger variety.

DR. RICARDO:—

He agreed with the comment made by Mr. Lawrence concerning the two-stroke engine, that the release pressure at the end of the expansion stroke would be far above the turbine pressure. If they could use the kinetic energy which was available directly on the turbine, so much the better; but his feeling was that the turbine would not like it, and he was not claiming any credit for that at all. If the turbine could face up to it, so much the better.

The effects of the exhaust impulses of one cylinder upon another were not very serious, and he was assuming that all cylinders were discharging into a considerable capacity.

AFTERNOON SESSION

In the Chair Sir FREDERICK HANDLEY PAGE.

THE APPLICATION OF THE GAS TURBINE IN ITS FORMS TO THE FIELD OF COMMERCIAL AVIATION

by

R. M. CLARKSON, A.C.G.I., B.Sc., Fellow

1. INTRODUCTION.

THE DEVELOPMENT of the gas turbine is so rapid and the thermo-dynamic ingenuity which is being lavished upon it at the present time is so imaginative and varied that the words " in its forms " which appear in the title to this paper can mean as much or as little as you please. Partly because I want to limit the scope of this paper to developments which might be expected to be in service within the next five years, and partly because I am frankly not sufficiently acquainted with the characteristics of many of its more advanced forms, I am going to confine myself to a discussion of the effects upon the speed and economy of commercial aviation of the two simplest and immediate variants of the gas turbine—the simple jet-producing turbine and the simple propeller-driving turbine.

2. Before proceeding to a more quantitative study of the subject I am going to examine briefly several of those power unit characteristics which are of particular interest to the civil operator and try and make general comparisons between the piston and turbine engines.

2.1. *Weight, Fuel Consumption and Drag.*

As is well known, the chief advantages of the gas turbine compared with the piston engine are considerably lighter weight and lower drag; the fuel consumption may be competitive with the piston engine or may be more, depending upon the form of gas turbine employed and upon the speed of flight at which it is operated.

The following table compares several different types of engines suitable for transport aircraft and gives an indication of what

Type of Power Unit.	Installed Weight.	*Specific Consumption.	Drag—lb. at 100 ft./sec.
1. Piston — air - cooled radial type.	2.0 lb./take-off b.h.p.	0.46 lb./cruising b.h.p./hr.	38 lb. per 3,000 take-off b.h.p.
2. Piston—liquid-cooled.	2.1 lb./take-off b.h.p.	0.53 lb./cruising b.h.p./hr.	22 lb. per 3,000 take-off b.h.p.
3. Propeller-driving centrifugal gas turbine.	1.2 lb./equivalent take-off b.h.p.	0.5 lb./equivalent cruising b.h.p./hr.	13 lb. per 3,000 equivalent take-off b.h.p.
4. Propeller-driving axial gas turbine—advanced type.	0.75 lb./equivalent take-off b.h.p.	0.45 lb./equivalent cruising b.h.p./hr.	9 lb. per 3,000 equivalent take-off b.h.p.
5. Simple jet — centrifugal.	0.5 lb./lb. static thrust.	†1.05 lb./lb. static thrust.	5 lb. per 5,000 lb. static thrust.
6. Simple jet—axial—advanced type.	0.35 lb./lb. static thrust.	‡0.90 lb./lb. static thrust.	0 lb. per 5,000 lb. static thrust.

* At 300 m.p.h. unless otherwise stated.

† Gives 0.65 lb./equivalent b.h.p. at 500 m.p.h.

‡ Gives 0.56 lb./equivalent b.h.p. at 500 m.p.h.

Fig. 1

we may expect from turbine engines compared with existing piston engines. Engine No. 5 is in being, No. 3 very nearly so, and Nos. 4 and 6 might be available to the operator within the compass of time covered by this paper.

The table is intended to give a general indication of possible trends rather than a precise description of engine capabilities and the figures given should not be associated too literally with the types of engines against which they appear, but should be regarded rather as stages in a development programme.

For example, the relative fuel consumption of the engines labelled " centrifugal " and " axial " respectively are not substantiated by current practical experience, since no axial engine to date has succeeded in beating the centrifugal; nevertheless it is the general opinion of engine designers that the theoretical claims for the axial engine should ultimately be realised in the course of development.

Similarly, the fuel consumptions of the engines labelled " air-cooled " and " liquid-cooled " are functions of the engine design formula rather than of the method of cooling, being representative respectively of the large easy breathing engine on the one hand, and of the small much supercharged engine on the other. It is to some extent incidental that the method of cooling is different in the two types.

We shall see later in the paper what happens when we design aeroplanes to take these various types of prime-movers.

2.2. *Reliability, Serviceability, Maintenance, etc.*

I do not think that anybody can possibly doubt that ultimately the gas turbine will be superior to the piston engine in these respects. Among the factors which give grounds for this belief are:—

Relative mechanical simplicity with no intermittent or reciprocating motions, and no sliding friction.

Absence of ancillary equipment, chiefly ignition (absence of carburettors is partly offset by the introduction of a rather complicated fuel system).

The symmetry and homogeneity of its internal thermal conditions with complete absence of temperature fluctuations.

Elimination of cooling as a major installation problem.

The suppression of many lubrication difficulties.

The operator will naturally and quite justifiably reply, " Yes, but what do you mean by the word ' ultimately '?" He wants an acceptable degree of reliability and maintenance under airline operating conditions delivered to him with the engine, not several years afterwards, *i.e.*, the engine with its enormous technical and economic advantages is of little use to him unless it is accompanied by a standard of reliability at least equal to that which he has learnt to expect from the piston engine. I believe that there is a very real problem here to be tackled energetically and imaginatively by the engine and aircraft manufacturers in co-operation with the airline operators if we are to ensure that the word " ultimately " means something acceptable to the operator.

A word now about maximum power outputs for reliable operation; with piston engines about 50 per cent. of take-off power seems to be about as much as any operator is willing to take out of his engines, and he does this at about 80 per cent. of take-off r.p.m. Any encroachment on these figures reflects itself immediately upon overhaul periods and reliability. It is the combination of r.p.m. (piston speed) and i.m.e.p. which really determines the wear and tear on the engine, and the 50 per cent. rule is only a rough way of expressing this. The curve on Fig. 2 labelled " piston " is a constant i.m.e.p. curve representing this condition and passing through 50 per cent. of take-off power at 25,000 ft.

Engine manufacturers seem to be agreed that a comparable figure for the gas turbine

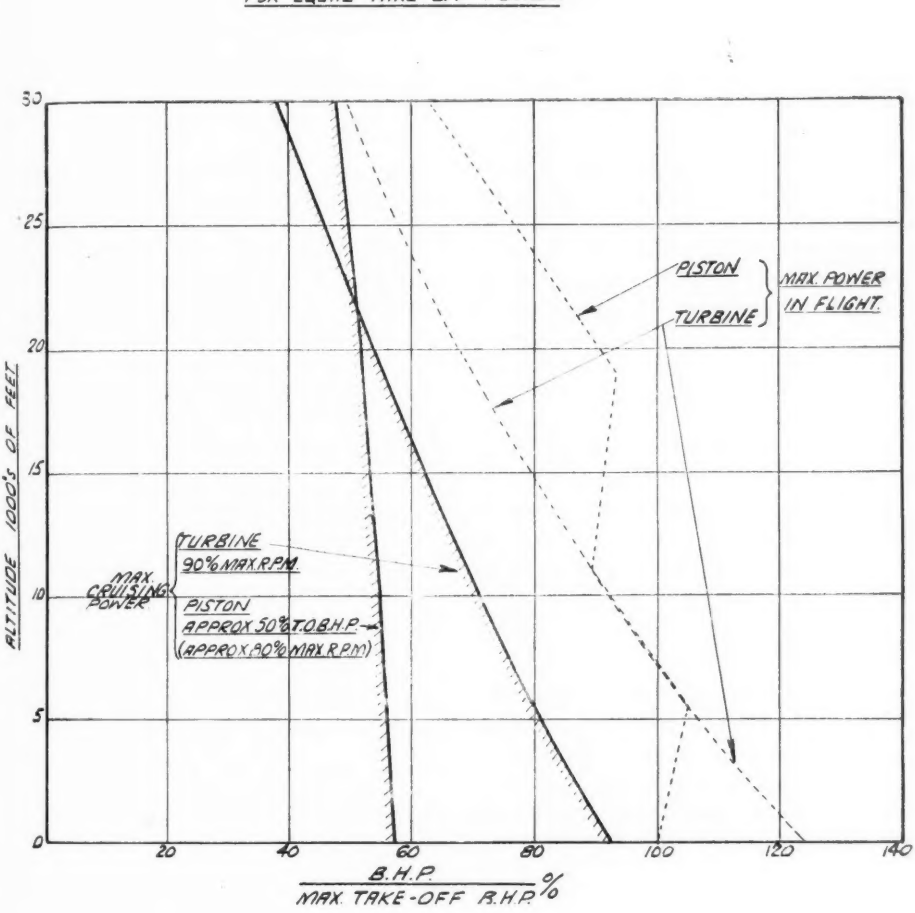


Fig. 2

is represented by 90 per cent. of maximum r.p.m.; under these conditions the cruising power output at any altitude is about 80 per cent. of the maximum power output at that altitude, and the temperature 100-150°C. lower, centrifugal stresses being about 20 per cent. lower. This output as a fraction of take-off output is shown by the curve marked " turbine " in Fig. 2.

It is seen that the two curves are roughly coincident at around 25,000 ft., but that at lower altitudes much greater fractional power outputs can be taken from the turbine, if required, for equal engine life.

2.3. *First Cost.*

Very similar remarks apply as for maintenance, *i.e.*, there are very good reasons, because of its relative simplicity, why the turbine engine should be relatively cheaper to produce than its piston counterpart, particularly as outputs increase. There is opportunity here for the exercise of design and production ingenuity in the particular

manufacturing problems of the gas turbine.

First cost is, fortunately, not one of the most important factors when intensive operation is practised (utilisation of 3,000 hours and upwards per annum).

2.4. *Noise.*

The noise of the gas turbine is of a rather irritating character, but I believe that it will not be unduly troublesome to passengers enclosed in a pressure cabin with reasonable sound-proofing. This point has yet to be proved, however. What I think may be more troublesome is the annoyance caused to passengers and others on and around airports, the noise nuisance being almost at its worst under taxying and idling conditions. However, not all existing gas turbines are equally noisy and there would appear to be some case for a little research directed to the understanding of the whys and wherefores of noise in gas turbines with a view to endeavouring to design some of the noise out of them.

2.5. *Vibration.*

With the simple jet engine low frequency vibration is, as we all know, non-existent. This is evidenced by the fitting of vibrators to dash boards in order to avoid sluggishness of the instruments and the fact that all sorts of liberties can be taken in the engine installation with the design of fittings, brackets, etc., etc., which couldn't be tolerated for a moment with piston engines. There is, however, a very high frequency vibration. Whether this will prove troublesome to passengers I cannot say; it seems unlikely.

Whether or not the vibration characteristics of the propeller-driving gas turbine will be substantially better than those of the piston engine seems at the moment to be in some doubt, and depends on how much of the vibration to which we have been accustomed is attributable to the propeller. We can say, however, that thanks to the nature of the new prime-mover the vibration characteristics on the whole cannot be worse and are likely to be a lot better. This is important to the passenger because, as is generally agreed, on a long flight vibration becomes more irritating with the passage of time, whereas one tends to get accustomed to noise.

2.6. *Paraffin.*

Besides providing far greater safety from normal fire hazard this also makes fuel jettisoning a much safer and more straightforward proposition. Its low volatility, objectionable smell, and creeping property, taken together however, do not recommend it for civil purposes. We were worried about this initially, but experience with fighters to date, on which no special precautions have been taken, seems to be reasonably satisfactory in this respect. It is, however, a point which must be watched with passenger aeroplanes.

The present bulk price of 100 octane petrol in this country is 1/6 per gallon without tax, the corresponding figure for pool burning oil is 8d., so that whatever the taxation policy may be in the future (and the ruling tax at the moment is 9d. for petrol and 1d. for paraffin) there seems little doubt that the new fuel will be substantially cheaper than the old. This is of vital importance to the operator whose fuel cost represents about 30 or 40 per cent. of his direct operating cost.

For the purpose of this paper I have taken petrol at 2/- per gallon and pool burning oil at 2/3rds of this price, *i.e.*, 1/4 per gallon; the relative cost per B.T.U. being thus in the ratio 1:0.6.

Among miscellaneous points, one might mention in passing that the starting up of gas turbines under extremes of climate looks like being easier and more automatic than is the case with the piston engine. It should be noted also that the gas turbine can provide a plentiful and duplicated supply of hot, high pressure air for cabin pressurisation, if, from all points of view, this proves to be the most acceptable method.

3. PARTICULAR GAS TURBINE APPLICATIONS.

It is now proposed to examine quantitatively one or two representative types of commercial aeroplane when designed (*a*) for piston engines and (*b*) for gas turbines.

3.1. *Medium Twin Feeder Line Aeroplane.*

We are required to meet the following specification:—

Pay load with 500 miles still-air range at 5,000 ft.—3,000 lb.

Seating for 12 passengers.

Crew—2.

Satisfactory compliance with A.R.B. safety requirements on a warm day.

With engines having the following characteristics:—

	Piston.	Propeller-Driving Turbine.
Installed weight per equivalent take-off h.p.	2.4 lb./h.p.	1.5 lb./h.p.
Cruising specific fuel consumption	0.49 lb./b.h.p./hr.	0.52 lb./equivalent b.h.p./hr.
Cruising condition	50 per cent. of take-off b.h.p.	90 per cent. of take-off r.p.m. (72 per cent. of take-off power).

We arrive at aeroplanes having the characteristics shown in Fig. 3.

Direct operating cost includes the following items:—

Fuel and oil	Petrol 2/- per gallon + 6 per cent. for oil. Paraffin 1/4 per gallon + 1 per cent. for oil.
Maintenance :	
Airframe	£1 10s. per aircraft flying hour per 10,000 lb. of airframe weight.
Engine	£1 per aircraft flying hour per 1,000 take-off b.h.p. (for piston and turbine).
Crew	£1,600 per annum and 850 crew flying hours per annum.
Depreciation :	
Airframe	5 years' life with 25 per cent. residual value.
Engine	2½ years' life with 25 per cent. residual value.
Insurance	8 per cent. of the first cost.
Interest on investment	5 per cent. of the first cost.

Passenger service, overheads, etc., are not included in direct operating cost.

The first cost of the airframe is taken at £2 10s. per lb. of airframe weight, and of the engines £4 per take-off h.p. (for piston and turbine); an allowance for spares carried of 20 per cent. of the first cost of the complete aircraft has been made.

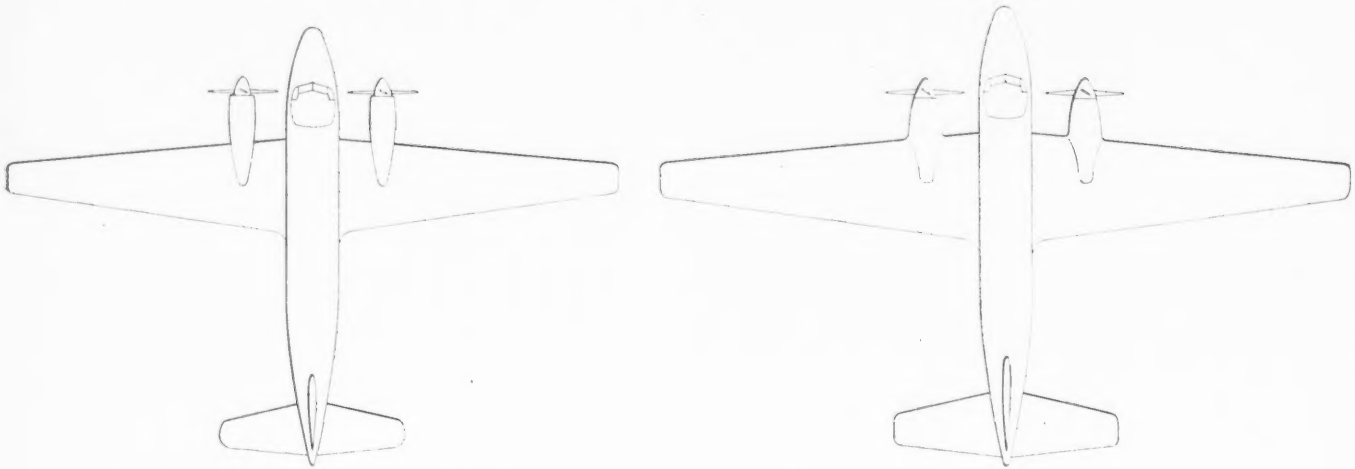
A utilisation of 2,000 hours per annum has been taken.

We see that the turbine aeroplane, to carry the same pay load as the piston version, is 22 per cent. smaller, 18 per cent. cheaper, 22 per cent. lighter, 16 per cent. faster, requires 21 per cent. less installed power, is 32 per cent. cheaper to run and can perform 16 per cent. more work in a year.

It is the substantial saving in power unit weight per horse-power possible with the turbine which is the chief cause of these improvements.

3.2. *Aircraft for the Private Owner.*

We have just dealt with the case of the propeller-driving turbine of around 500 h.p. output; it is necessary now to say a word about smaller engines around the 150 h.p. class. There is little, if any, practical experience in this field as yet. My belief is that considerations of ruggedness, low first cost, and reliability will result in an engine of not very competitive economy. More-



ALL UP WEIGHT	10,600 LB.	13,500 LB.
INSTALLED POWER (TAKE OFF)	2X550 B.H.P.	2X700 B.H.P.
GROSS WING AREA	390 SQ. FT.	500 SQ. FT.
OVERALL SPAN	61 FT.	69 FT.
WING LOADING	27 LB/SQ. FT.	27 LB/SQ. FT.
FUEL FOR 500 MILES	131 GALS.	141 GALS.
CRUISING SPEED	215 M.P.H.	185 M.P.H.
PAY LOAD	3,000 LB.	3,000 LB.
TON MILES OF PAYLOAD PER GALLON OF FUEL	5·7	5·4
TON MILES OF PAYLOAD PER HOUR	288	248
FIRST COST OF COMPLETE AIRCRAFT	£15,500	£19,000
DIRECT OPERATING COST PER TON MILE OF PAYLOAD	9·4d.	13·9d.

FIG. 3

A comparison between a medium twin feeder line aeroplane designed for gas turbines and piston engines.

over, the huge gear reduction needed will tend to make the engine bulkier and heavier than might be expected.

I think, therefore, that we must not look for any significant quantitative improvement over the piston engine, meaning by this that the combined effects of weight, drag and consumption on aircraft design will not be particularly startling in this field, it being remembered that these aeroplanes must operate at sea level where the matching of aircraft L/D and engine specific consumption is least favourable to the turbine.

The more practical advantages of the turbine—in regard to noise, vibration, simplicity, etc.—will naturally be available in full measure to the private owner and club flier and will amply justify the introduction of the new prime-mover in this field. Furthermore, owing to the higher fractional cruising power which can be used with impunity at low altitudes, cruising speeds can be substantially higher than is now the case.

It has been asked whether the simple jet-producing engine can be made available to the more sporting private owner (400-450 m.p.h. cruising); I think the answer depends upon how high he is willing to fly and how far he wants to go. If he wants a safe operating range of 300 or 400 miles at a moderate altitude and the ability to go under the weather when necessary, then I do not see much hope of giving him anything but a rather wasteful conveyance with poor take-off, even using an engine of the type of No. 6 in Fig. 1. Cruising speeds in excess of 250 m.p.h. will, however, be easily within his reach with propeller-driving turbines.

3.3. *Long-Range Empire Airliners.*

Skipping now several intermediate classes of civil aeroplanes we pass on to a study of aircraft designed to cruise non-stop over stage lengths of 2,200 miles*[1] which entails a still air range of upwards of 3,000 miles varying somewhat with cruising speed.

For the purpose of this investigation I have imposed the following design requirements:—

Cruising altitude—not less than 25,000 ft.
Take-off under tropical conditions—not more than 1,500 yards to clear 50 ft.
Max. wing loading for take-off—70 lb./sq. ft.
Max. wing loading for landing—55 lb./sq. ft.

A range of cruising speeds from approximately 300 to 500 miles per hour has been covered and engines Nos. 1, 2, 3 and 4 of Fig. 1 separately investigated.

For simplicity we have taken for the 300 m.p.h. case an aeroplane of approximately 100,000 lb. all-up weight, 150 ft. span, and 1,800 sq. ft. wing area; in passing to the higher cruising speeds more power has been installed and all-up weight allowed to rise subject to the design conditions being met, structure weight, etc., being suitably adjusted, and fuselage dimensions and passenger amenities*[2] suited to the resulting pay loads. At the high speed end of the scale some reduction in span was found to be desirable, the wing area being unchanged. At the 300 m.p.h. end, the cruising altitude and take-off requirements design the aeroplane; as the speed rises, however, the loading limitations tend to take charge. All the aircraft are cruised at a speed 15 per cent. above that for maximum L/D at 50 per cent. of take-off power for piston engines and 90 per cent. of maximum r.p.m. (45 per cent. of take-off power) for turbines; and the cruising altitude is higher with the faster aeroplanes.

Relatively conservative assumptions regarding laminar flow have been made:—
Tractor layouts with transition at 0.1 c in the slipstream and 0.3 c outside it.

*[1] Against a 50 m.p.h. head wind plus a 450 mile alternative aerodrome allowance.

*[2] The scale of passenger amenities assumed throughout is roughly of Tudor II Standard, becoming a little less spacious as the cruising speed rises and trip-time falls.

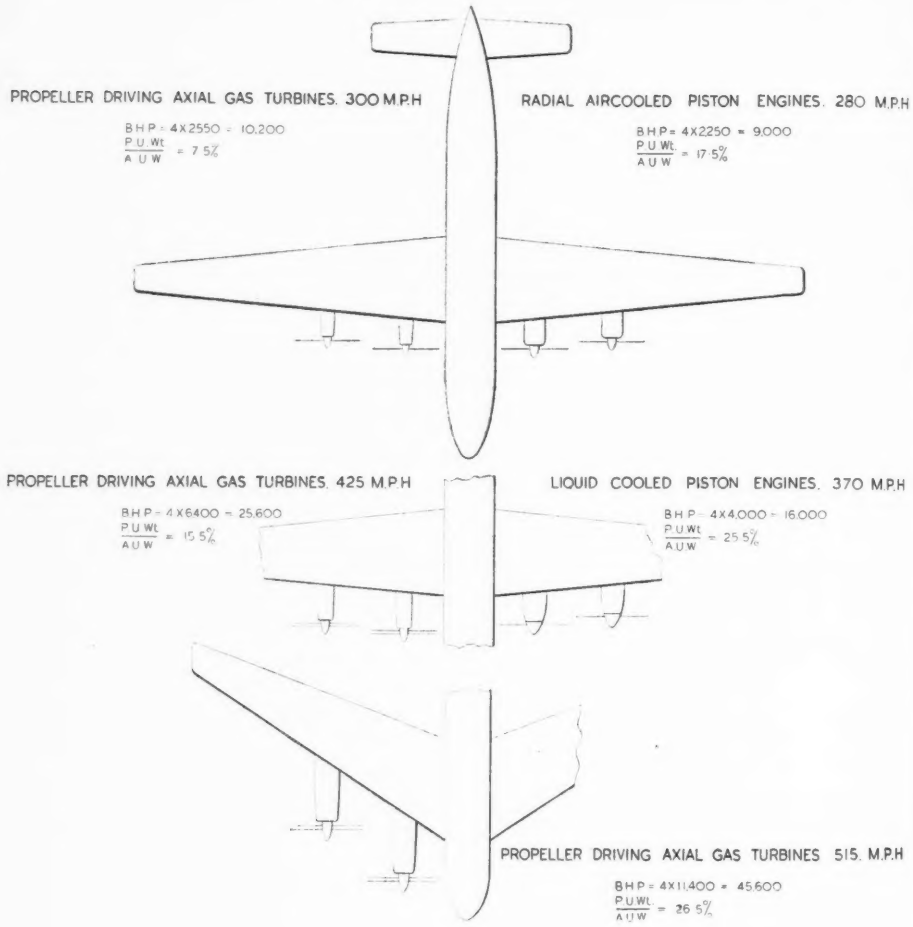

PROPELLER DRIVING AXIAL GAS TURBINES. 300 M.P.H
B.H.P = 4 X 2550 = 10,200
P.U.Wt / A.U.W = 7.5%
RADIAL AIRCOOLED PISTON ENGINES. 280 M.P.H
B.H.P = 4 X 2250 = 9,000
P.U.Wt / A.U.W = 17.5%
PROPELLER DRIVING AXIAL GAS TURBINES. 425 M.P.H
B.H.P = 4 X 6400 = 25,600
P.U.Wt / A.U.W = 15.5%
LIQUID COOLED PISTON ENGINES. 370 M.P.H
B.H.P = 4 X 4,000 = 16,000
P.U.Wt / A.U.W = 25.5%
PROPELLER DRIVING AXIAL GAS TURBINES 515. M.P.H
B.H.P = 4 X 11,400 = 45,600
P.U.Wt / A.U.W = 26.5%

Fig. 4

Fig. 4 gives a rough idea of the size and weight of some of the power units installed at different cruising speeds.

Fig. 5, which results from this study, shows pay load attainable in aeroplanes of approximately constant size when designed for different cruising speeds, and powered with different types of engines. It is seen that very considerable increases in either pay load or speed are attainable with the new forms of power unit, and this is due to the fact that we are moving into a new regime where power is cheap in terms of weight and drag. The rise of the curves to a maximum is due to the increase of loading and the subsequent fall due to the imposition of a landing loading limitation; if this were relaxed better results at high speeds could be achieved, but this would lead to abnormally large fuselages in the region of 400-450 m.p.h.

Better speed and pay load characteristics might be obtained with the piston engine if the complications of the exhaust-driven

turbo-supercharger were accepted. The point marked "E.T.," which assumes no weight or drag penalty, is an optimistic estimate.

If an overall transition at 60 per cent. of the chord could be achieved at no cost in weight point "A" would move to point "T."

The aeroplane at point "B" is interesting; it has four engines of 11,500 b.h.p. each. The power loading of the whole aeroplane is under 3 lb./h.p., propeller efficiency has fallen to about 70 per cent. and will probably fall rapidly with increasing speed; furthermore, compressibility drag rise is beginning to set in on the aeroplane, necessitating the incorporation of sweepback. It seems unlikely that the engines for this aeroplane could be available within five years.

It is necessary at this stage to say a word about the simple jet engine for commercial aviation. Its extreme simplicity and light weight recommend it strongly; its high speed possibilities make it operationally most suitable for long-range work, but it is technically least suited to this duty—poor take-off thrust and high fuel consumption. If used for short-range operation it must either be cruised at a high altitude with considerable loss of effective cruising speed due to time lost in climbing up and coming down, or at

EFFECT OF CRUISING SPEED ON PAYLOAD WITH VARIOUS ENGINES IN AIRCRAFT OF A GIVEN SIZE.

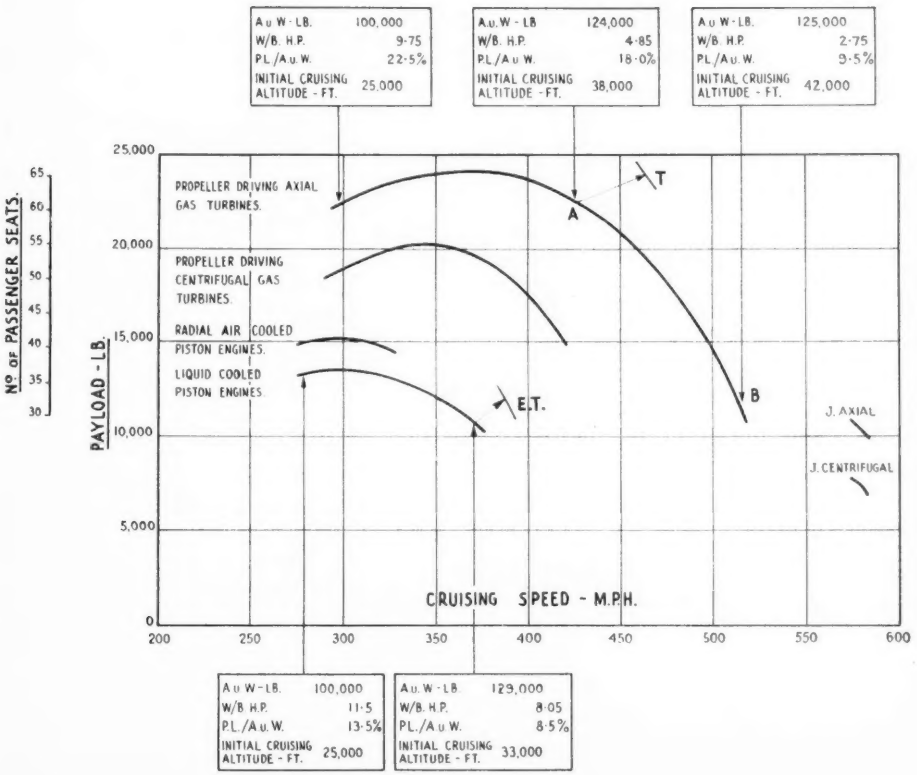


Fig. 5

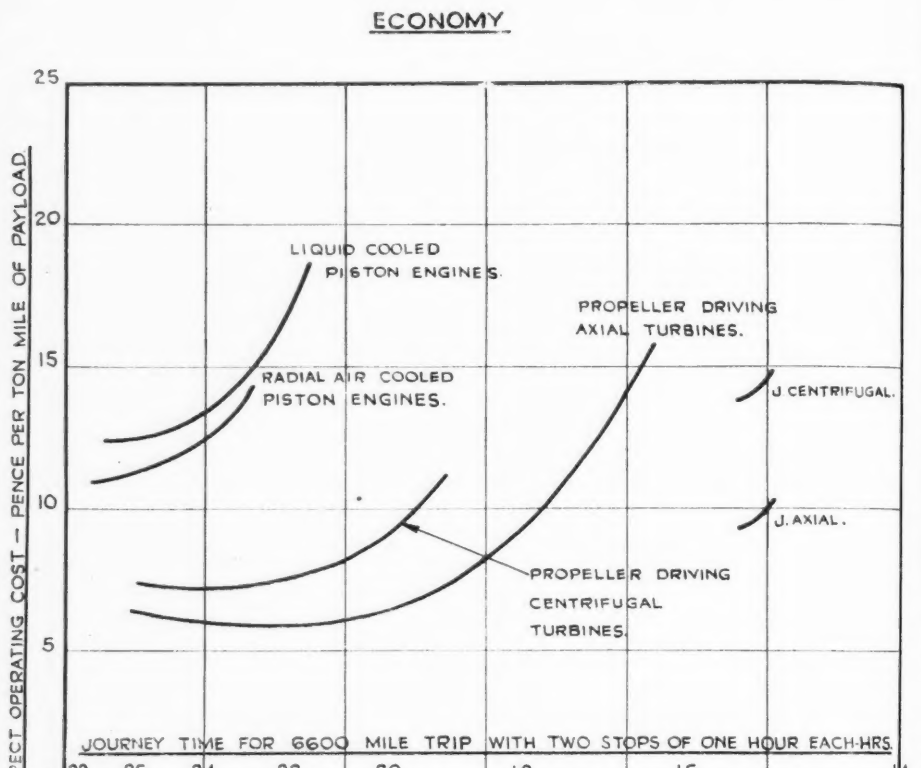


Fig 6

a more moderate altitude with very excessive fuel consumption. Neither of these alternatives is very satisfactory.

In order to overcome its technical disadvantages when operated over ranges such as we are considering in this section of the paper, some form of assistance for take-off would be required, possibly rockets, and a relative degree of austerity in passenger amenities, crew complement, etc., must be accepted. The operation of the aeroplane would be of a somewhat specialised nature, and its design would demand the solution of a number of acute problems resulting from the high Mach number encountered. Nevertheless, if these difficulties and limitations can be overcome, cruising speeds can be pushed up beyond that of aeroplane B in Fig. 6, as shown by the two curves marked "J centrifugal" and "J axial," which represent aeroplanes somewhat smaller than those under consideration, but as large as it would seem prudent to consider in view of the difficulties.

Any future improvement in the calorific value per lb. of fuel which is not accompanied by an undue reduction in density would be of particular value to this aeroplane; and flight refuelling may have some claim for consideration over longer ranges.

We pass on now to a consideration of the cost of operation of these aeroplanes. Fig.

6 shows direct operating cost per ton-mile of pay load plotted against effective cruising speed, which is the cruising speed made good over a 2,200 mile run in still air after making allowance for climb and descent and quarter hour for stand-off, taxying, etc. As would be expected, these adjustments have a more serious effect on the fast aeroplanes than on the slow ones—the 500 m.p.h. aeroplane loses 70 m.p.h. of effective cruising speed; the 300 m.p.h. one 20 m.p.h.

Along the bottom of the graph has been put a scale of total time for a journey of 6,600 miles in three hops, allowing 1 hour on the ground per stop. This is about the distance to either South Africa or South America and half the distance to Australia. This scale is included because it is really time saved rather than cruising speed for which the passenger is paying.

The method of operating cost calculation is similar to that used for the feeder line aeroplane of section 3.1, but maintenance costs per unit of airframe weight and engine power have been increased by about 33 per cent. due to greater complexity; crew cost has been increased appropriately; insurance raised from 8 per cent. to 12 per cent.; the first cost of the airframe per unit of tare weight increased by about 20 per cent.; and the spares allowance increased from 20 per cent. to 30 per cent. A utilisation of 3,000 hours per annum has been taken.

If the cost of paraffin were taken the same as petrol, the direct operating costs of the turbine aeroplanes would be increased by about 1d. per ton-mile. To obtain a rough idea of the total operating cost inclusive of overheads and passenger service and based on a 60 per cent. load factor, the costs in Fig. 7 should be doubled and then divided by 0.6; the figure for the 400 m.p.h. axial turbine aeroplane would thus become about 27d., or taking ten passengers to the ton, 2.7d. per passenger-mile as the price at which transport might be sold to the public.

Fig. 7 shows, for these aeroplanes, the earning capacity or the ton-miles of pay load which can be shifted per annum per aircraft. This is equal to the product of pay load, effective cruising speed and utilisation.

3.4. *Trans-Ocean and Long-Range Work.*

For operation from trans-ocean aerodromes we can allow loadings to run up to about 80 lb./sq. ft. and take-offs to about 2,000 yards to clear 50 ft., provided that the cruising altitude does not fall below 25,000 ft. Fig. 8 shows curves of pay load against still-air range* for several aeroplanes of fixed weight and size. The fuselage capacities have been adjusted to their pay loads along the curves, so that any point on a curve is an aeroplane designed to carry that particular pay load over that particular range.

The Atlantic requirement is marked on the figure and needs a still-air range of approximately 4,700 miles. I cannot see that still-air ranges greatly in excess of about 5,000 miles are of much practical value to commercial aviation on this planet, but if anyone wants to travel non-stop for distances approaching 7,000 miles or so (*i.e.*, S.A.R. =8,000 miles approximately) then it would appear to be quite possible to do so with reasonable economy, as is indicated by the figures of pay load/A.U.W. per cent. marked along the curves.

If, however, 5,000 miles is approximately a maximum practical still-air range for commercial purposes, then it appears that the straightforward propeller-driving turbine can make a very good showing, and it may be asked whether commercial aviation can profitably use the more advanced forms of heat engine giving specific consumptions approaching 0.3 lb./b.h.p./hr., but involving greater complexity, weight and bulk, with both turbine and piston components; it being remembered that economy in practical

* Still-air range in this paper is the distance the aeroplane can travel after allowance for fuel used on climb and descent (distance credited to range), taxying, etc., and half hour stand-off. It is somewhat less than the product of cruising m.p.g. x fuel capacity which is generally called still-air range, but which we call ultimate range.

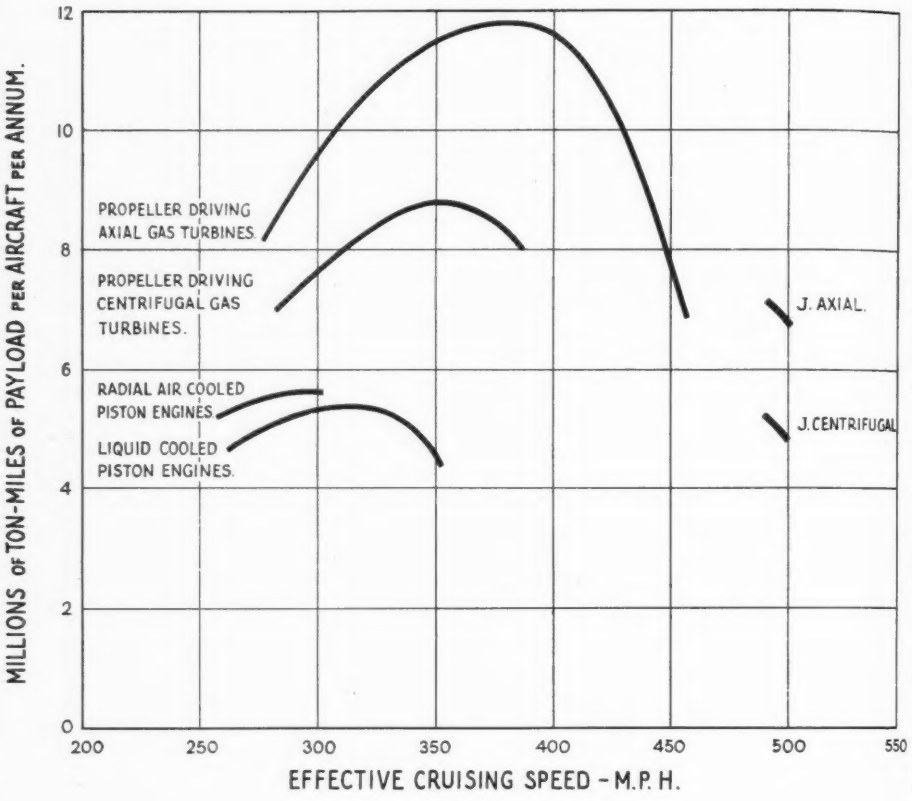


Fig. 7

operation involves all these factors in addition to mere fuel economy.

4. CONCLUSION.

It is impossible within the compass of a paper of this nature to cover adequately the impact of the gas turbine upon all classes of commercial aircraft. General methods of analysis are sometimes apt to lead to erroneous conclusions. I have, therefore, confined myself to one or two types and examined them in detail, taking account of all relevant factors, and thereby keeping as close an eye as possible on practical considerations.

Many general conclusions can, I think, be drawn; I will only mention here a few which come to mind:—

Higher speeds with higher unit pay loads will become economically possible.

As speeds rises, increasing care is demanded of the operator to ensure that the increased speed appears in the form of a saving of trip time.

For a given unit pay load aeroplanes will tend to get smaller; this means that:

Fuselages will tend to get relatively larger, *i.e.*, we are moving in the direction of the "flying container" rather than towards the "flying wing."

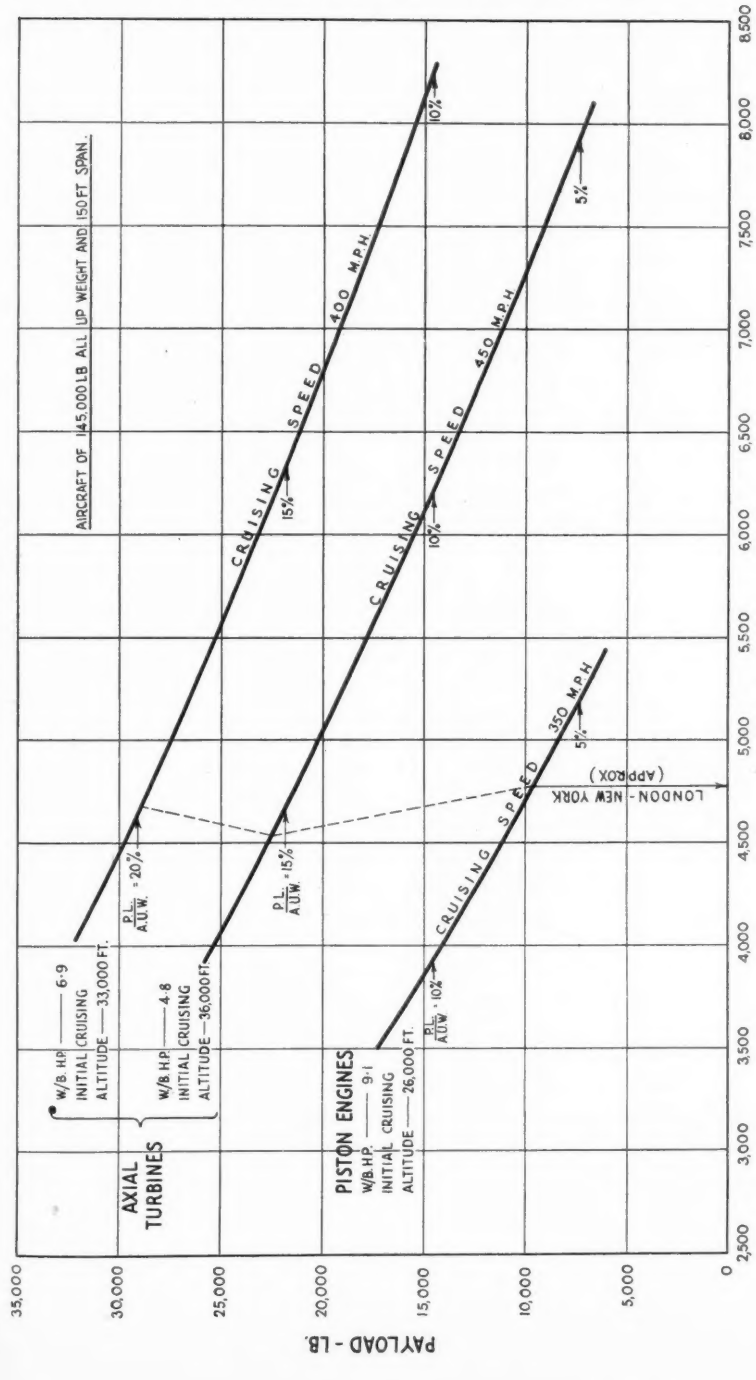

LONG RANGE
AIRCRAFT OF 145,000 LB ALL UP WEIGHT AND 150 FT SPAN.
AXIAL TURBINES
W/B H.P. —— 6·9
INITIAL CRUISING ALTITUDE — 33,000 FT.
W/B H.P. —— 4·8
INITIAL CRUISING ALTITUDE — 36,000 FT.
PISTON ENGINES
W/B H.P. —— 9·1
INITIAL CRUISING ALTITUDE — 26,000 FT.
CRUISING SPEED 400 M.P.H
CRUISING SPEED 450 M.P.H
CRUISING SPEED 350 M.P.H
P.L./A.U.W. = 20%
P.L./A.U.W. = 15%
P.L./A.U.W. = 10%
15%
10%
5%
10%
5%
LONDON - NEW YORK (APPROX)
PAYLOAD - LB.
STILL AIR RANGE - MILES.
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0
2,500
3,000
3,500
4,000
4,500
5,000
5,500
6,000
6,500
7,000
7,500
8,000
8,500

Fig. 8

As speed rises, take-off (with propeller-driving engines) becomes relatively better and ceases to design aeroplanes or aerodromes. Wing loading becomes the limiting factor in so far as it determines comfortable stand-off and approach speeds; and any method of permitting higher wing loadings, such as boundary layer control, may be very important.

The simple jet can make a contribution to commercial aviation provided certain aircraft problems can be overcome and some re-orientation of outlook is acceptable to operators.

In conclusion I wish to offer a special word of thanks to those members of my staff who have assisted in the preparation of this paper, in particular Mr. Herrod-Hempsall and Mr. Newman, without whose help the paper would not have been possible.

My thanks are also due to others, in particular Mr. C. G. Walker, for reading the proofs and offering valuable suggestions.

DISCUSSION

MR. G. H. LEE (Handley Page, Ltd., Associate Fellow): What was the basis of comparison for the aeroplanes dealt with in Fig. 5? Were the aeroplanes compared on a basis of equal wing area? On a basis of equal all-up weight, the peaks in the pay load curves would occur at speeds lower than those shown.

Asking at what height the author considered that jet propelled aircraft should operate, he said that it seemed, from work with which he had been associated, that it paid to fly as high as possible, provided that the true airspeed did not become so high as to give shock stall troubles and that the pressurising difficulties could be overcome. Could the author indicate what he considered to be a suitable height for jet propelled transport aircraft?

With regard to the swept-back wing, how did the author fix the maximum permissible thickness/chord ratio in relation to the Mach number at which it was desired to fly, *i.e.*, how had he allowed for the increase in critical Mach number with sweep back? Also, since sweep back made the attainment of high maximum lift coefficient difficult, the wing area of those swept-back wings that were designed by landing speed should be greater than that of the corresponding conventional wing; had this been allowed for in making the comparison between conventional aircraft and those with swept-back wings?

MR. H. PEARSON (Rolls-Royce, Ltd.): It had been stated that the gas turbine engine made rather an irritating noise. Perhaps Mr. Clarkson was speaking of his own gas turbine; tests on the turbine with which he was concerned showed that it was some 30 decibels quieter, at all frequencies, than a piston engine of equivalent performance. That meant that the turbine was considerably quieter than the piston engine.

A second heresy was the reference in the paper to the poor take-off power of the jet engine. The jet engine had an enormous take-off power. For example, there was 8,000 lb. take-off thrust in the case of the Meteor. He felt quite sure that, in the case of the aircraft which Mr. Clarkson was considering, for flights of more than 3,000 miles at an altitude of 4,000 ft., the take-off power would be ample.

MR. R. S. STAFFORD (Handley Page, Ltd., Fellow): The long-range aeroplanes considered by Mr. Clarkson had the conventional 4-in-line power plant arrangement, and there would be great difficulty in satisfying the Air Registration Board's requirements for control during take-off.

When the large fins required for a reasonable safety speed with present power loadings of around 11 lb. per h.p. were considered, the designer was faced with a major problem in dealing with the offset

thrust at 6 lb. per h.p. for Mr. Clarkson's 400 h.p. propeller turbine aeroplane. He had wisely refrained from indicating what his aeroplane looked like in side elevation.

Because of small overall diameter, the axial propeller turbine was suitable for installation in coupled units, and by using clutches or free wheel devices a most favourable and compact nacelle design was evolved in which, for preference, a pair of contra-rotating propellers could be driven through a common gear train.

The arrangement had several important advantages in addition to that of eliminating large offset thrusts of the conventional outboard engines, *e.g.*, the contra-rotating propellers could be driven by one turbine without the attendant drag increase normally associated with feathering or a high degree of yaw. That permitted of flexibility in operation, with better economy at heights lower than the 25,000 ft. enumerated by Mr. Clarkson, and might prove to be an advantage for certain forms of operation to enable the long-range aeroplane to operate with reasonable economy on medium stages. That was important because the propeller turbine was relatively inefficient when throttled.

With a common gearbox, the need for duplication of auxiliaries was eliminated, and there was an overall saving in drag because of the smaller nacelle wing interference and smaller area in the slipstream.

He suggested that the advantages of the coupled axial propeller turbine were so outstanding that the development of the necessary gearboxes should proceed on a priority equal to that of the turbines themselves.

THE PRESIDENT: Inviting Mr. Bulleid (President-Elect of the Institution of Mechanical Engineers, and Chief Engineer to the Southern Railway) to preside during the remainder of the session, recalled that at a recent three-day conference on the gas turbine, held by the Institution of Mechanical Engineers, he had been invited, as President of the Royal Aeronautical Society, to preside on the second day, and had gladly accepted the invitation.

It was a pleasure to welcome Mr. Bulleid, and the Society was gratified that, in spite of his many duties, he had consented to preside.

MR. BULLEID, formally occupying the Chair, said he accepted the invitation, not only as a compliment to the Institution of Mechanical Engineers, but also as a locomotive engineer, who crawled about at a modest 70 m.p.h. Perhaps it was thought he would introduce a little sanity into a realm which wa quite fantastic!

THE APPLICATION OF JET PROPULSION TO MILITARY AIRCRAFT

by

W. G. CARTER, Fellow

THE association of gas turbines with aircraft designed to make effective use of the special characteristics of jet propulsion has brought the trend of development into a state of transition and uneasy experiment. Already speeds equivalent to a low level Mach number of 0.80 have been recorded under observed conditions. This has been done by a standard twin-jet fighter not specially designed to accomplish speed exceeding a low level Mach number of 0.66.

The general handling qualities of the air-

craft have been good and although changes in the aerodynamic characteristics are just beginning to be noticeable, these are regarded as moderate in effect and generally in line with predictions which had been made. It may therefore be possible to make more advanced explorations into the transonic region with similar twin-jet installations.

The percentage increase in drag over the low speed value, as shown by Fig. 1, gives a clear indication that the prospects are there if successfully exploited. The curve is not necessarily an accurate representation as the available thrust has yet to be calibrated in flight. Up to a Mach number of 0.825 it may be regarded as reasonably accurate and the extrapolation beyond this figure is the best guess that can be made at the present time.

This curve provides a clear indication that the twin-jet arrangement somewhat belies the first impression that because of wing nacelles

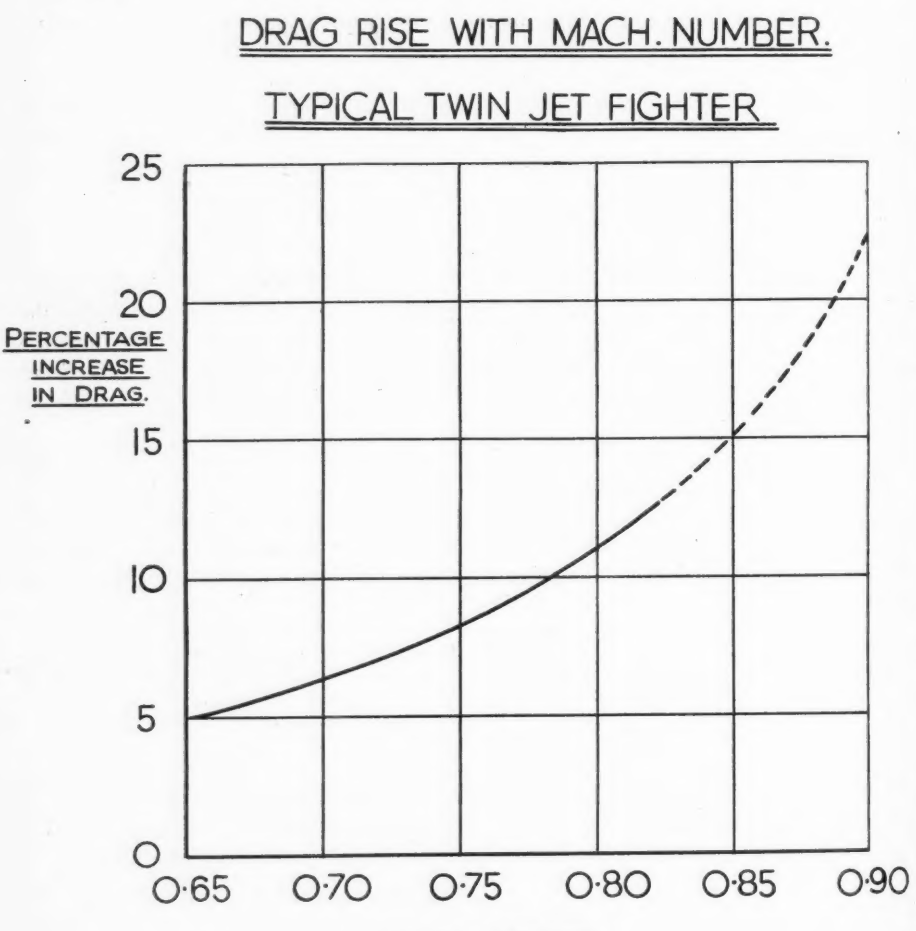


Fig. 1

it may not be so favourable for speed development as compared with its counterpart, the single jet fighter. The low speed drag value of the twin will obviously be higher, perhaps as much as 50 per cent. higher, than the single jet machine designed to satisfy the same general operational requirements.

But percentage increase in drag is the critical factor and experience is beginning to show that wing nacelles do not greatly influence the rise in drag due to compressibility effects. Like the fuselage, they are three dimensional bodies and, if precautions are observed to harmonise the associated air flow characteristics of wing and nacelle, there seems to be no reason to suppose that flight velocities exceeding sonic conditions could not be accomplished with engines on the wings.

The main concern with the twin-jet arrangement is to minimise the severity of buffeting effects due to turbulence. Substantial improvements in this direction have been made by lengthening the nacelles of the Gloster Meteor, a feature combining to improve their fineness ratio and separate more widely peak suctions of wing and nacelle as separate items. This, at one step, put the limiting Mach number up to 0.84 whereas unfavourable effects had been recorded with short nacelles at a Mach number of 0.75.

No doubt a further increase in Mach number could be achieved by lengthening the nacelles another stage, at the same time improving their shape so as to delay shock wave effects. It would be a great advantage if research along these lines could be explored in the wind tunnel, but at high Mach number it is impracticable to do these tests except by full-scale flight.

The work done at the R.A.E., which was effective up to a Mach number of 0.80, was of incalculable value in providing information without which the process of designing the Gloster E28 and the Meteor could hardly have proceeded on a satisfactory basis.

With engines installed on the wings it may be possible to accommodate more thrust in terms of all-up weight than could be done with the single jet fighter, or a three-engined arrangement could be considered to get even better results in improving the thrust-weight-ratio. This over-abundance of thrust, so far as fighter types are concerned, is required for climbing performance rather than for speed. As an indication of the trend in this direction, the Gloster Meteor now has a combined thrust of 7,000 lb.

At one time 4,000 lb. thrust was looked upon as a reasonable provision for aircraft of this type and a corresponding figure of 3,000 lb. good enough for the single jet machine. Now the outlook is that however much thrust can be crammed in, it is unlikely to be more than can be used effectively, especially for climbing performance to great altitudes in the shortest possible time. This has become necessary in order to intercept bomber or reconnaissance types which with jet engines will be able to cruise at twice the speed and twice the height that has hitherto been possible. As climbing characteristics depend on the thrust-weight value of the aircraft, the present trend of development will mostly be concerned with giving this the highest possible value.

The outlook is that this can best be done by having two engines instead of one, but before this premise can be firmly established it will be necessary to provide jet engines giving much more thrust per unit frontal area than is obtainable from those having centrifugal compressors. These are inevitably bulky in terms of diameter as compared with the axial and there is no room for corpulence in the jet fighter, whether it is propelled by one or more jets.

The Rolls-Royce Nene engine, rated at 4,500 lb. thrust, is already outside the diameter limit for fighter aircraft nacelles, so that the most significant comparison which can be made between various engines concerns their respective thrust value in terms

of frontal area more than any other installational feature.

In making these comparisons there is not much to go on at the present time. The background is scanty enough with centrifugal engines, but with those having axial flow compressors, it is almost non-existent. The first, and so far the only, axials produced in this country were those designed by Metro-Vickers and flown in one of the Meteor prototypes. As the first British experimental type it could be compared on the basis of performance with the Whittle engine as flown in the Gloster E28 jet demonstration aircraft. This Whittle engine has since been developed to give about three times as much thrust. If the same impressive achievement can also be made to apply to the axial engine, over 7,000 lb. thrust should be obtainable from the same frontal area.

Looked upon from another point of view, the Rolls-Royce Derwent and Nene engines could be examined to get some idea of the present outlook as regards the centrifugal jet engine. After providing sufficient clearance outside the normal diameter of the Derwent so that air can enter the rear face of the double-sided compressor, this increases the effective installed diameter to 48 in., giving a thrust of about 280 lb./sq. foot. The same process applied to the Nene also gives a similar value. No doubt both engines are capable of being developed to provide more thrust than their present rating and a guess will be made that the centrifugal may eventually give about 400 lb. thrust per unit area.

When the axial type is considered there seems to be no reason why the diameter should much exceed that of the air-intake orifice. For the same thrust as the Nene, this diameter will be about 27 in. Some further increase is to be expected over the combustion chambers and, making allowance for this and for structural considerations, the effective nacelle diameter should not exceed 33 in., indicating a thrust value of about 750 lb. per square foot as compared with 400 lb. for the centrifugal engine. This may be an optimistic estimate, but if it can be done, the twin-jet fighter may well have an overwhelming advantage.

These slim engines also provide the opportunity to consider their side-by-side installation in a fuselage widened sufficiently for this purpose but the question of balancing the aircraft satisfactorily becomes difficult with so much weight aft of where the centre of gravity is best positioned. The available space to accommodate fuel is also severely restricted with this arrangement, while the problem involved in ducting the air supply to the engine is an embarrassing feature of the structural assembly.

There is, of course, ample scope for considering other alternative arrangements and it may be preferred to put the engines in nacelles forming part of the fuselage. This gets over the difficulty of balancing and provides room for plenty of fuel capacity between the engines. It introduces a difficult problem at the air-intakes and if conditions here are not good, the breathing capacity of the engine is compromised and thrust may be reduced under high speed conditions. One of the outstanding advantages of the twin-jet arrangement is that ducting problems do not have to be taken into account.

The question of engine accessibility is also a matter for special consideration. With a fuselage installation it is not an easy matter to get at the engine for servicing or replacement. The Gloster E28 was most inconvenient in this respect, a relatively unimportant item as it was a non-Service type. In this instance it was necessary to remove a large number of screws from a cover forming part of the fuselage structure. It can be imagined that unless careful attention is given to the detail design relating to this feature, it would not be regarded as very acceptable.

These maintainance features are greatly enhanced when twin booms are used as an alternative arrangement for supporting the tail surface. The de Havilland Vampire is a good example of this method of construc-

tion but as development proceeds, it may be that the structural characteristics of booms are unsuitable for association with high Mach number velocities. Flight under these conditions can induce very heavy downloads on the tail. These might be as much as the weight of the aircraft and exceptional stiffness of the fuselage structure becomes necessary to eliminate the possibility of adverse aerodynamic effects.

Another jet fighter, the Lockheed Shooting Star, makes provision for disconnecting the rear fuselage as a complete unit in order to provide access to the engine nacelles. At one time this might have been regarded as a drastic expedient but it seems to have worked out well in practice. The twin-jet fighter provides an easy solution to these problems concerned with engine accessibility and maintenance.

Some curves are given in Fig. 2 emphasising the outlook on climbing performance. Similar and comparable information concerning speed has not been included as this aspect is more concerned with other features of design, such as aerodynamic refinement and special facilities to maintain precision control of the aircraft under all conditions. These matters relate to the uneasy experiments now rapidly coming into the aeronautical picture, but rates of climb may be very much further advanced before these formidable problems become too obtrusive.

The curve " A " represents a typical rate of climb performance for the Gloster Mark IV Meteor. This aircraft has a thrust weight ratio of 0.5 and climbs to 30,000 feet in five minutes. It represents about the best climbing performance for the present-day jet fighter.

If a thrust weight ratio of unity could be developed for a similar type of aircraft, rates of climb as shown by curve " B " would become possible. This can only be done by using axial flow engines developed to provide a thrust of about 700 lb. per square foot of nacelle frontal area. The climbing performance of one of these engines in a single jet fighter would not be nearly so good.

The alternative power installation for high

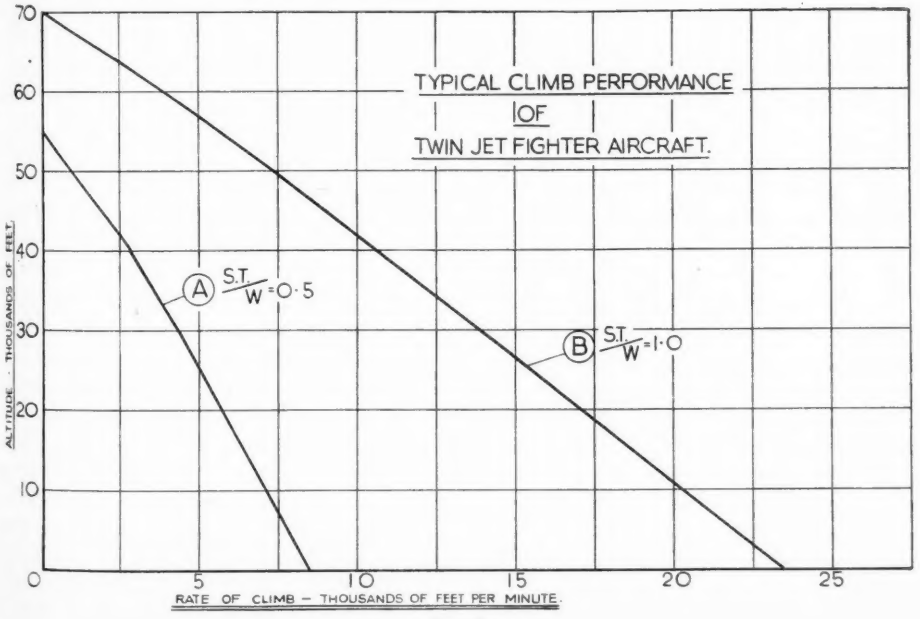


Fig. 2

altitude interception would comprise rocket assistance. For this purpose jet engines on the wings make it convenient to put the rocket combustion chamber at the rear end of the fuselage. As a type, the rocket-cum-jet interceptor combines the advantage of out-climbing the conventional jet fighter with the possibility of cruising facilities at the desired altitude. How far the trend of development may proceed in this direction depends largely on to what extent it may be possible to improve gas turbine jet installations so that these can function satisfactorily without rocket assistance.

Some of the work done in Germany has been much concerned with unconventional arrangements in order to get the utmost performance from a given thrust. These are aspects which cannot be neglected if they lead towards a more efficient jet installation. As such, these developments are worthy of careful study and possibly, in some instances, verifying by experimental means. On the other hand, the presumed advantage may be more than outweighed by the prospect of sacrificing good handling qualities over some parts of the speed range. It is vitally important that the aircraft should respond to precision control under all conditions.

It can be seen that the working out of a new equilibrium between attack and defence has only just begun and that the problems associated with this outlook have become greatly intensified as the tempo of events has been accelerated. More effective armament installations are also likely to be required and these may profoundly influence the general trend of design and development. At no other time in the history of aeronautical events have so many intricate and formidable problems been presented for solution.

In this brief review only a few of the aspects concerned with the application of jet propulsion to military aircraft have been mentioned. There are many secondary considerations no less important than those which relate more to the fundamental aspects of design. These associated effects mostly involve the safety and comfort of the pilot, a matter for special consideration now that speed and altitude ranges have been so greatly increased. However good the aircraft may be as a means of transport for offensive weapons, so much depends upon the man in making the most effective use of the military machine.

DISCUSSION

AIR COMMODORE F. R. BANKS (M.O.S., Fellow): He had been wondering where, eventually, the engines would be placed in very high speed aircraft and he had felt for some time that there would be considerable difficulty in fitting the engine in the fuselage, at the same time having to make room for fuel and armament, etc.

Barring military aircraft of the semi-rocket type—which might be more accurately described as piloted weapons—he felt that the practical interceptor machine with gas turbines would not go much beyond a performance equivalent to 0.87 Mach number. To do this would require considerable power, but for the interceptor it would require this power mainly for improving the rate of climb. And, since it was doubtful whether they could get better than 3,000 to 3,300 lb. of static thrust within a circle of 24 in. diameter, it looked as if the engines would have to be put on the wings.

MR. H. PEARSON (Rolls-Royce, Ltd.): He associated himself with the remarks of Mr. Carter concerning the twin-engined aircraft, but took exception to the use of the paper for the purposes of an attack on the centrifugal engine as opposed to the axial. He criticised the thrust figures quoted in the paper for the centrifugal engine as being too low, since the paper assumed that air had to be led round the engine to reach the rear

edge. This was no longer the case and figures of thrust per unit frontal area for modern centrifugal engines were about 380 lb. per sq. ft., higher in fact than the German axial jet engines.

MR. F. PILLING (Gas Turbine Dept., Metropolitan-Vickers Electrical Co., Ltd., Associate Fellow): The brilliant picture of the future painted for the gas turbine was too good to be true! It must be remembered that the gas turbine was just another prime mover and would, therefore, have a sphere of operations in which it would be supreme. Outside that sphere other prime movers would have strong claims.

He referred to the advent of the steam turbine and the enthusiasm with which its supporters prophesied the end of the piston engine. Yet more than 40 years after Parsons sailed his "Turbinia," the tramp steamer still used the multi-expansion reciprocating engine.

Similarly, with the introduction of the large Diesel engine the end of all other prime movers was forecast. But it was again proved that each type had its own range of usefulness and all could work side-by-side with more amity than nations.

Now, the gas turbine could produce huge powers in a single engine of light weight, small bulk and excellent reliability. These were the fundamentals to be considered in aircraft work.

Having received the power unit the aircraft designer must next obtain the highest propulsive efficiency with the lowest drag installation. The method of converting heat energy to effective thrust would depend on the flight speed of the aeroplane. If a cruising speed of 300 to 350 m.p.h. with a maximum speed of, say, 450 m.p.h. was sufficient then the airscrew was the best means of propulsion. But if speeds exceeding 500 m.p.h. were needed the designer must first turn to the jet.

Between these two methods came the combination of fan and jet known as the Augmentor, but there was no time to introduce this subject. It should be followed up, as it gave the advantages of light weight and small bulk for its power, allied with less specific fuel consumption and greater propulsive efficiency at take-off and climb than the simple jet. It promised to fill a gap between the high range of airscrew use and the low range of the simple jet. It also introduced the principle of the separate "power turbine" to drive the fan independently of the compressor-turbine unit.

When considering the gas turbine and airscrew, all applications reviewed at the discussion implied a tractor airscrew with reduction gearing hung on the front of a modified jet unit. Much was made of the difficulties of ensuring good airflow at the intake of the compressor. This led to the question whether this was the correct way to solve the problem. It was the *quickest* way as it was possible to adapt an existing type, but the matter was not simply one of taking a drive from the front end of the compressor. There were difficulties enough in matching the characteristics of compressor and turbine without adding the complication of again matching these to the varying requirements of an airscrew.

The best solution was to use the compressor-turbine combination of the jet unit as a hot gas generator which served a second or "power" turbine to drive the airscrew. This turbine could be placed immediately behind the first. Not only did this ease the turbine design problem, but it allowed an immediate reduction in r.p.m. since the power turbine could operate at much lower speeds than the turbine driving the compressor. Consequently the final reduction gears for the airscrew became a more reasonable proposition.

With the simple tractor versions shown at the discussion the power turbine arrangement would need a central shaft running through the generator unit from the turbine at the

rear to the reduction gears at the front. This shaft would necessarily be long in relation to its diameter so that critical speeds would impose further difficulties.

Why not use a pusher airscrew which would avoid both the air intake interference and the transmission shaft troubles? If the separate power turbine scheme was accepted, the layout called for an airscrew mounted behind the wing with the power unit exhaust duct bifurcated and swept outwards each side of the shaft drive. It was possible in future, with very large aircraft and engine installations buried in the wing, that the power turbine might be a separate unit from the gas turbine, the two connected by ducts; but this foreshadowed some of the complications which several speakers feared as accompanying the need for higher efficiencies.

The gas turbine was a unit of large power. Yet the suggestion was made that two engines should be coupled to drive one airscrew. Apart from the enormous problems of matching two independent turbines, was this not the wrong approach? Within the restrictions imposed by the aircraft designer even the piston engine could deliver more horse power than could be absorbed efficiently by the airscrew. Why not reverse the suggestion and have one large gas turbine driving two airscrews?

There was a logical reason for the British concentration on centrifugal compressors up to the present; it followed from a policy of evolution. The centrifugal unit had reached a high degree of efficiency in normal engine superchargers and an extensive knowledge of design and manufacture was available for immediate application to the gas turbine. It was natural that such experience should be used in the war-time race for success while fundamental research proceeded at a slower pace on the little known characteristics of the axial type. The development of the axial compressor and still more of the annular combustion chamber had been a long-term policy which would pay dividends in the near future with the advent of higher compression ratios and larger powers.

A sudden switch from centrifugal to axial compressors, or from flame tube to annular combustion chambers was not to be expected as large resources in design and manufacturing facilities had been built up and these could not be abandoned economically.

The compounded engine projected by Dr. Ricardo was another method of utilising existing knowledge to improve the present day state of the gas turbine. But the mechanical complications and possible losses in transfer pipes and ducts might detract from its value. The merits of Dr. Ricardo's scheme from an installation point of view could not be fully assessed until drawings of the installation layout were available.

Fuel consumption was still argued on a specific basis of lb./b.h.p. or lb./lb. thrust in unit time. It was amusing to find the engineer so faithful to this cliché when he never used any other unit than miles per gallon when referring to a motor car. The consumption of all aircraft engines should be compared on m.p.g. It was impossible to evaluate equivalent thrust horse power of the jet engine unless the speed factor was introduced. Likewise no true value of fuel used was possible without consideration of the distance flown.

As Mr. Clarkson proved, when comparing aircraft it was necessary to consider the weight of engine plus weight of fuel for the given range. It might be that for short-range aircraft, where engine weight was of more importance than fuel weight, the centrifugal type was best because it had at present a lower engine weight. On the other hand, for long range where weight of fuel was of greater importance than engine weight, the higher efficiency of the axial type would meet the case better, especially with the added advantage of lower drag due to its smaller diameter.

All large gas turbines needed high output from the starter motor. Not only the inertia

of the rotating parts had to be overcome, as added to this were the pumping loads as the engine accelerated and the compressor handled more and more air. The engine designer would favour the electric motor as it was more compact and lighter than alternatives and the power supply lines were simple. But when the weight and size of batteries to meet British starting requirements were added the installation became prohibitive. Petrol engine starters were in course of development and formed a practical method of catering for repeated starts from a self-contained system which might be reasonably carried in an aeroplane. The disadvantages were the use of petrol and the need for a separate fuel system, and probably a remote starting system for the starter motor itself.

MR. J. E. SERBY (D.D./A.R.D. (S), Fellow): The papers and discussion had emphasised the value of the turbine engine driving a propeller, as well as, in extreme cases, the plain jet engine. It was important to remember the extent of the problem of taking air into a turbine engine driving a propeller; they were only beginning to face that problem. In the past they had been fortunate, for it had so happened that with jet engines they had been able to use a very simple air intake. The taking of the air straight into the engine was obviously ideal; but once they placed a propeller in front of the engine and tried to lead the air intake around the roots of the propeller blades they were in difficulties.

Although the development periods in respect of some of the jet engines had been extraordinarily short, they had to look forward to far longer development periods in the future. There was always extra work on gearing involved, and it seemed that that would lengthen the development period a great deal.

With regard to noise from the gas turbine, he had found the noise to be extremely trying from the point of view of the person on the ground.

No reference had been made in the discussion to the German jet engine work, but in many, if not all, respects the German jet engine was less efficient than the British, but there were lessons to be learned from a study of the German work.

GROUP-CAPTAIN A. F. SCROGGS (Fellow): It was true that the axial type of compressor would have the smaller overall diameter; and if it were necessary to have a long nacelle anyway, from the point of view of accommodating it, the extra length of the axial compressor did not matter very much, but might be some disadvantage because of its more widely distributed mass. That applied to fighter aircraft of the types they had been flying until now with jets; and the long length of heavy metal might affect the manœuvrability.

Dr. Hooker seemed to think there was nothing very much in the vulnerability of the jet engine, but whereas the records of the last war showed that in numerous cases piston engines, particularly air-cooled engines, had brought aircraft home and apparently had been running merrily, although in fact they had suffered an extraordinary amount of damage, it was difficult to imagine that a turbine engine would keep going after being hit by only a bullet. Moreover, if an aircraft were equipped with three or four piston engines, it would very likely get home even if one of those engines were out of action. In the case of the turbine engine, if the whole thing blazed up into a mass of flame, things were not so good!

Speakers had been talking cheerfully of altitudes of 50,000 ft. and speeds of 600 or more m.p.h. So far they had only two types of jet aircraft in service, and there was no prospect of a jet propeller-driven aircraft for a considerable time ahead. Many problems had yet to be solved; he did not think they could really say yet that they knew what

those problems were going to be, let alone how to solve them.

For the efficient operation of a jet propelled aircraft for commercial purposes it would be essential to have a pressure cabin, and there were serious problems in that connection alone. He believed that civilian passengers did not like going up and down at more than 200 or 300 ft. per minute; so that it was necessary to evolve a really effective pressure cabin, for this reason also.

MR. R. H. SPIKES (Armstrong Siddeley Motors, Ltd.): Many defects had to be dealt with before reduction-gears for gas turbines were fully developed.

In his experience—and he and his colleagues had quite a lot of running experience of propeller turbines—the noise they emitted was much less than that of the jet unit; it was also, in his opinion, much less than that of the piston engine, and it should be less objectionable.

On the question of the axial flow compressor versus the centrifugal for the propeller, in his opinion there was no doubt that the axial flow type was the one for the job. With the centrifugal type, using 4/1 compression ratio and with the temperatures they should be able to attain when using modern materials, they would not get near the optimum thermal efficiency. For higher ratios there had not been a two-stage centrifugal compressor yet which gave comparable efficiency to an axial flow compressor.

MAJOR F. B. HALFORD (de Havilland Aircraft Co., Ltd., Fellow): He had still a great interest in the piston engine as well as the gas turbine, and felt, with Air Commodore Banks, that a note of warning was necessary lest they fell into a trap. Dr. Hooker, in his admirable exposition of the gas turbine, had dealt faithfully with that pigmy, the plain, straightforward centrifugal turbine. Dr. Ricardo, in his typically lucid way, had given a description of that more abstemious giant, the compound engine; Mr. Carter had also talked about the merits of the axial, which he had never used!

If the Germans had gone to the centrifugal jet instead of the axial, considering that they had started seriously before the war, they might have knocked Great Britain out of the air, because they would probably have got there so much more quickly. In this country, in America and elsewhere, the axial flow type, on paper, was impressive. If Germany had been led more ably from the top—and his remarks were no reflection on the abilities of scientists and engineers—they would not have been allowed to miss out steps in between; he believed Great Britain was led better from the top, and that it was because they had kept both feet on the ground that they were where they were to-day.

He did not agree that the turbine was as reliable as the piston except in extreme cases, where they could afford, as in the R.A.F., to change engines overnight. The airline operator wanted more than that; he pleaded that they should make sure not to try to sell something before it had been obtained.

MR. PILLING: The Germans, having begun with the centrifugal machine, had discarded it because of the higher efficiency of the axial. It was also interesting to note that they had discarded the flame tube and had gone over to the annular combustion chamber, he believed for the same reason.

MAJOR HALFORD: Had the German axial engines a lower specific weight and lower specific fuel consumption than any centrifugal engine being used by the Allies?

AIR COMMODORE BANKS: For a given bulk weight, the German gas turbines gave only about half the thrust of their British equivalents and in getting it consumed considerably more fuel. The German axial flow compressors were not particularly good, but

were better than their centrifugal ones, which were rather bad.

MR. H. PEARSON: The point which was always maintained in respect of the axial blower was that it gave more thrust per unit of frontal area. The thrust per unit of frontal area given by the German engine was slightly inferior to that of the British centrifugal.

MR. PILLING: He agreed that the German axial flow engines were inferior to the British centrifugal; but he did not agree that the British axial flow engines were also inferior to the British centrifugal. The centrifugal engine would be lighter, for a given power, than the axial flow type, because the centrifugal was a shorter engine and was also much faster running. Those were two fundamental engineering points. But he was confident that the axial flow type would be more efficient than the centrifugal. Already it was admitted that to increase the efficiency of the centrifugal type it was necessary to go to more than one stage in the blower, and that was an inefficient way of dealing with air. The axial flow compressor would be more efficient than the centrifugal for the higher compression ratios.

MR. J. P. HERRIOT (Rolls-Royce, Ltd.): During the discussion he felt the engine people had had far too long an innings, while the aircraft contingent had been sitting back. He imagined that there could be no doubt in the minds of those present that the development of the turbine engine, whether it be of the simple jet or the gas turbine airscrew type, was a much quicker proposition than the more conventional piston engine. Dr. Hooker had shown that the Derwent V engine had been developed from the drawing board up to running at full thrust in something like five months.

This constituted a very fine contribution to the development of gas turbines, but it did not show the whole picture, as a great deal of the valuable time gained in the quick development of the engine had been wasted because of the non-availability of prototype aircraft in which to fly these engines. Something like 18 months after it was first run up to full power the only aircraft in which the Nene engine had flown was the American "Shooting Star." They were a good jump ahead of the Americans in producing jet propulsion engines, but for some time to come the Americans would beat them in producing the prototype aircraft.

Much more attention than formerly should be given in this country to the rapid production of prototype aircraft. There were at present good jet propulsion engines available which had run many hundreds of hours on the test bench, but would shortly become obsolete for want of aircraft to fly them in, and because bigger and more powerful types of engines were being developed. The good old days when the aircraft manufacturer had almost unlimited time to design and build his prototype because it took approximately 4-5 years to fully develop a piston engine had gone and the goal in view must be that the aircraft must keep pace with the engine.

He had recently read an article by members of the medical profession in which were listed all the terrible things that could happen to pilots and passengers at 45,000 ft., and it seemed to him that they were as good as dead before they left the ground. Serious attention should be given to the problem of evolving an efficient and effective pressure cabin, the absence of which was seriously jeopardising and delaying the development of the jet engine under altitude conditions.

The axial type of compressor suffered considerably in performance if dirt was allowed to build up on the compressor blades; and although the engine manufacturer might spend a considerable time in evolving efficient oil seals for the compressor front bearing, the airscrew would probably undo all the good work. Intensive development to evolve better oil seals for airscrews was, in his

opinion, important so far as the axial gas turbine was concerned.

MR. J. HODGE (Power Jets, Ltd., Graduate): The discrepancy in efficiency between the axial and the centrifugal types of compressors was not fundamental, but was due largely to the difficulties of calculating and of finding out what was happening in the centrifugal type. With the axial type they could calculate by the extension of the ordinary aerofoil theory what would happen to it, and could make tests; but with the centrifugal type it was an extremely complicated technical problem. When they had more time to study the matter they should be able to improve the efficiency of the centrifugal type a great deal; it had been improved by perhaps 10 per cent. since just before the war and another five or six per cent. improvement soon was by no means unlikely.

The necessity for developing an effective pressure cabin was not a problem peculiar to jet propelled aircraft. It seemed to him that any aircraft which had to fly considerable distances would need to fly above the weather; so that the need for a pressure cabin applied, whatever type of engine was used, the chief difference being in the degree of pressurisation necessary.

EVENING SESSION

DR. H. ROXBEE COX presided at the beginning of the final session and was later succeeded by the President, Sir Frederick Handley Page. On the motion of Dr. Roxbee Cox, a hearty vote of thanks was accorded to Mr. Bulleid for presiding during the afternoon session.

AIR COMMODORE BANKS (M.O.S., Fellow), responding to an invitation to comment on the position regarding centrifugal and axial types of compressor, in order to put it in proper perspective, said that he was in rather a privileged position to make this point, being responsible for engine research and development on behalf of the Ministry.

The arguments in the afternoon session were similar to those of the past twenty-five years or more on the relative merits of liquid- and air-cooled piston engines. There was no point in starting a wrangle along similar lines on centrifugal and axial compressors. They had more experience of centrifugal than of axial compressors but obviously the axial type had many advantages. It was possible now to design an axial compressor of about 6 : 1 overall pressure ratio at sea level, giving an adiabatic efficiency of about 85 per cent., and they could get a centrifugal blower giving 73 to 75 per cent adiabatic efficiency at a pressure ratio in the region of 5 : 1.

The axial compressor was probably more critical to damage than the centrifugal but it was the business of the operator to see that they were not damaged.

A serious loss in efficiency and reduction of thrust had sometimes been experienced on the test bed due to industrial dirt getting on the blades of an axial compressor; but this was not the case in the air and they had flown axial compressor type engines in the bomb bays of Lancasters in order to examine their characteristics in flight. No trouble because of dirt had occurred, and no problems were expected to arise in airline service.

Both types of compressor were being developed and there was no question of any arguments " for or against " at this time. But the axial type offered many advantages, such as high pressure ratios at relatively high efficiencies and also high air flows.

One of the difficulties of the annular combustion chamber was that sections of it could not be tested and then related to the

complete combustion chamber. The combustion chamber had to be tested as a whole, which involved an air supply equivalent to the whole air requirement of the engine. In the case of separate or multiple combustion chambers, they could test one unit and then assess the whole by the results obtained.

He had given warnings earlier (in the morning discussion) because he did not wish it to be assumed that transport aircraft would be flying at 600 m.p.h. to-morrow. At the same time, if someone started now to design an aircraft to fly at a height of, say, 35,000 ft., at a speed of 550 m.p.h., they could achieve such performance with the present jet turbines available by the time the aircraft was built and developed, *i.e.*, in about four or five years.

They should not expect to be able to buy kerosene (paraffin) at the same price as that at present charged for similar fuel for use in Valor Perfection stoves, for example. The problem of gas turbine fuels was a very real one from the economic and supply angles, and although gas turbines could no doubt be developed to burn any fuel within reason, it was difficult to say what the final fuel would be when considering its distribution throughout the world. The price of gas turbine fuels would not necessarily be low and if one took a figure of unity for present 100/130 grade petrol (for piston engines), then he suggested the price of the fuel for gas turbines would eventually be in the region of 0.8.

DR. J. SEDDON (Royal Aircraft Establishment). There seemed to be a certain amount of loose thinking as to the significance of the problem of leading the intake air efficiently past the propeller blade roots in the propeller-turbine combination. The two factors at stake were the actual loss of ram efficiency sustained at the compressor intake and the extent of the mal-distribution there.

The Royal Aircraft Establishment had planned model tests to investigate those matters, but there was lack of quantitative information from the engine side as to what the losses would really mean. If they were to chase the last 5 per cent. of ram recovery, he would agree fully with Mr. Serby that an intensive programme of research was required; but at the moment it was not clear that anything up to 20 per cent. loss of ram was worth worrying about at speeds below, say, 450 m.p.h., which presumably covered the most important range of application.

Could Dr. Hooker or others who were concerned with turbines give a lead as to how seriously they regarded the whole problem ?

MR. J. AHERNE-HERON (Associate): It was a pity that more comparisons had not been made between the German turbine efforts and the British. Judging from some of the remarks made during the discussion, there was little to be learned from the German turbine engine. Whereas the metallurgist, by developing many new materials, had made the turbine possible in this country, this was not so in Germany. There the aerodynamicist, by introducing cooling air in the blades, had made it possible to produce a turbine which worked. Development in Great Britain, while it had produced more efficient turbines to date, was limited by metallurgical advances, which it did not seem at all possible would take us beyond 1,200°C., whereas the German technique of using coolants seemed to offer—with considerable development—temperatures far beyond this.

Some form of cooling between the gases and the blades, or some form of lubrication, or some other fundamental approach, was necessary. He hoped that it could not be quite so complicated as the variable volume combustion chamber which Dr. Ricardo had suggested. A much longer step forward needed to be taken than just the request for another 50°, 60° or 100° of temperature

which they were contemplating at the moment.

Attention had been drawn to the point that "flying cans" would be the mode. With all due deference to Dr. Roxbee Cox, the flying wing would probably go out. Dr. Hooker had said that speed was essential if the jet were to become efficient. If that were so, they would probably go to a form of fuselage having stabilising wings with some boundary layer removal; if the attitude of the wing could be altered on landing and take-off without affecting the comfort of the passengers, that type of step forward might be better than the adoption of the flying wing.

MR. W. E. W. PETTER (English Electric Co., Ltd., Fellow). Dr. Hooker had shown the efficiency curve for the jet engine as a propellent crossing that of the turbine-propeller engine at a rather high speed, something over 500 m.p.h. But that was not the whole story. The weight of the turbine engine driving a propeller would be a great deal more than that of the jet engine, and the aircraft structure would have to be increased in size to carry that increased weight. The drag would be higher.

They had yet to see any aeroplane propelled by an airscrew with a drag coefficient of less than .02, whereas with the jet engine they had got down to .015. Therefore, it might very well be that the curves would cross at a speed nearer 400 m.p.h. If that were so, they should to-day be pushing on with the jet propelled aeroplane, for which they had the power plant available already, rather than wait for the turbine propeller-driven power plant, which had not yet arrived.

The pressure cabin presented a problem, but it was not one that could not be solved. It had been solved already in one or two military machines quite satisfactorily. They had produced one pressure cabin machine, and he had been disappointed to find that the Service did not wish to take it up because plenty of pilots were willing to fly for two or three hours at 40,000 ft. with no pressure at all. If that were so, they need not feel that more moderate altitudes would worry the ordinary passenger, provided that he was given some pressure and that adequate safeguards were made against sudden de-compression.

Let them achieve the lower fuel consumption of the turbine-driven unit later. Mr. Clarkson had shown that, with centrifugal jet engines, they could achieve a cost of about 15d. per ton-mile at a cruising speed of 500 m.p.h.; thus, they could attain, for the same cost per ton-mile, a cruising speed just about double that obtainable with the radial or water-cooled piston engine to-day. That represented a long step in the right direction. Later they would perhaps arrive at a figure of 7d. per ton-mile, with a rather lower cruising speed.

It was pleasing that things were becoming a little simpler at last; they were becoming altogether too complicated in the latest types of piston engines. But the engine weights provided a fair indication of the kind of effort required to develop a new engine. The weight of a pure jet engine, as compared with that of the aeroplane in which it had to be fitted—for example, the Meteor type—was small. One engine probably weighed less than the undercarriage; it certainly weighed less than the fully-equipped pressure cabin which must go with it; and probably it weighed one-third of the wing.

The aircraft people had a tougher job than the engine people. The engine people were not bothered with sudden changes of policy which affected the whole conception of their designs. If they would like to see rather more rapid progress with prototypes, he suggested that some of the engineers whom the engine people now employed, and who would become redundant as the result of the simplification of the engines,

might go over to the aircraft people, who would be very glad to employ them.

MR. I. C. McORAN CAMPBELL (Associate Fellow): The compound engine would apparently start to pay at a range of about 6,000—7,000 miles; he would like to hear from someone concerned with the operational side what was considered to be the optimum, for that would be a pointer as to the line of development, particularly with regard to the compound engine.

In Fig. 8 in Mr. Clarkson's paper, in which payload was plotted against still-air range, he was surprised that the three curves were nearly parallel. They indicated that, when using the piston engine, if the range were increased from 4,000 to 5,000 miles the fuel consumption would increase by 6,500 lb., and with the turbine engine a similar increase of fuel for the same increase of range would be required. How did that arise; was it due simply to the difference in speed, or what other factors bore on the subject?

MR. GOODWIN: What had Mr. Carter against the twin-engined fighter? In his remarks he dealt purely with the centrifugal turbine, since they did not appear to know very much about the axial in actual flying.

Nacelles on wings seemed to him to be unpleasant, however one regarded them. They added to the inertia of the machine, both in the roll and in the yawing case. Aerodynamically, they had to be placed so that the thrust was on the chord line of the wing, which gave rise to installation and servicing difficulties; and they did not look nice. If the engines were pushed into the fuselage, with the use of the twin-boom lay-out, easier service could be provided than if they were on the wing; further, they were already behind the fuselage, which itself caused drag, but which had to be there anyway.

There was something to be said for the central engine in the fuselage. But, taking the Meteor as an example, they split it up on each side of the main spar, so that there was not a straight run through. He compared it with the Vampire, and said there seemed to be about the same effect in both cases. They were having some rather unusual kinds of engines, and they must have unusual airframes to go with them.

The single-engined machine was less complicated, particularly since the fuel supply system presented quite a problem in the case of jet engines. The single-engined machine, therefore, was a little simpler to develop than was the twin-engined. The tendency was always to put the biggest engine they could get into fighters; if they had two engines, that just meant developing bigger fighters, and that seemed bad.

MR. P. F. CRAWLEY (Student): The time of development had been referred to as being an important factor for the airframe manufacturers at this time, because of the increase in the speed of development of engines. It seemed to him that much more intensive organisation for the development of aircraft was necessary, both for the prototype and, even more so, for the aircraft that followed.

The effect of a short development time bore greatly on the use of military aircraft. In a future war, an aircraft whose use in service was held up by, say, six months in comparison with its opponents, might be obsolete before entering the fray.

Mr. Clarkson had shown that speeds of 500—550 m.p.h. could be expected from long-range aircraft in the future. Due to the higher density of bombs compared with passenger and freight, the bomber fuselage would be smaller, giving appreciably higher speeds of 550—600 m.p.h. for these aircraft. All the evidence pointed to the fact that flight near and at the speed of sound would be fraught with control and stability difficulties, and they might assume that

fighter aircraft would be designed for either subsonic or supersonic operation.

In the former case the fighter would have great difficulty in catching up with an enemy bomber, due to its operation near its Mach number maximum. A fighter designed for supersonic speeds would be able to catch up with its prey, but would be unable to stay long with it as slowing down would involve passage through the sonic region, during which the machine would no longer be a sufficiently stable firing platform.

For supersonic bombers the problem would return to the present fighter supremacy, except that rocket propulsion would be necessary and the time intervals would be shorter. It might appear that on the score of invulnerability the bomber would be operated at a Mach number of about .85.

Considerably enhanced striking power would be demanded from the fighter, and he felt that this would radically alter the "fighter problem." The possibility of batteries of rocket projectiles as on the "Natter," might necessitate secondary changes greater than those caused by the actual installation of the jet unit.

Mr. Carter's paper appeared to be based on the incorrect hypothesis that increased thrust would be the essential fighter requirement. In fact, it would soon be the case that the power required to propel a machine at its critical Mach number even vertically, could be housed comfortably in a fuselage large enough to carry the required armament at these speeds.

They had been told that the prime reason for the use of the jet engine was its low installed weight per lb. of thrust available. Surely it was more important that without a great deal of difficulty they could derive enormous powers from it, rather than that they obtained the power cheaply in terms of weight? The enormous powers available opened up the possibility of using much larger aircraft, even flying wings large enough to give laminar flow, and about 10—15 per cent. thick. It was probable that that was where the gas turbine would lead us in the future.

MR. E. J. RICHARDS (Vickers-Armstrongs, Ltd., Associate Fellow): In considering the application of turbines to civil airlines, they should attach as much importance to the noise that would arise as to questions of performance, maintenance, and so forth. The passenger was conscious of the noise of an aircraft throughout the journey and would willingly sacrifice ten minutes or so on duration if the aircraft was comfortable from the noise point of view.

It was interesting to see how the noise on a propeller turbine aircraft was likely to differ from that with reciprocating engines. He had been amazed to hear Mr. Pearson's remark that the turbine was 30 decibels quieter than the piston engine; that difference was about equivalent to the difference between the noise on the Piccadilly Tube Railway and that on a fairly quiet motor car. He had some figures of measurements of noise, which admittedly were obtained on the test bench when measuring the efficiency of quietening, but these suggested that there was going to be little to choose between the noise of the two types.

One great snag with propeller noise which arose when using a turbine was the necessity to run at about 90 per cent. of maximum revs. for cruising; it was necessary to run at high revs. for take-off which meant high revs. and a resultant high noise level for cruising. Some of the loss at take-off which would arise from a reduction of tip speed could be overcome by using a much higher solidity, but he thought that this would only aggravate the already considerable difficulties which he felt were bound to occur in having air centres behind the roots of a propeller, especially with the axial type. This aspect of the problem had not been sufficiently stressed, particularly as the use

of small hubs put the root thickness chord ratios up considerably. In his academic days he had made tests of aerofoil sections of slightly larger than 30 per cent. thickness chord ratio which had given a negative lift up to 10° incidence at some Reynolds numbers. If this state of affairs occurred on blade roots, what sort of flow could be expected going into the compressor ?

Sufficient importance had not been attached to the possibility of using a two-speed gear to obtain the best conditions both at take-off and on cruising. While a compromise could, in most cases, be achieved by sacrificing something both on take-off and on noise, there was little doubt that a two-speed gear would allow the noise level to be reduced very considerably.

A further source of noise was that due directly to the flow over the fuselage and wings. This aerodynamic noise would probably be preponderant on high speed aircraft in the high frequency range and there might be a class of traveller who would prefer to travel more slowly, if this meant much less noise in the cabin.

He would like to see engine manufacturers considering the far back air entry. When the aircraft was considered as a whole it was not true that the ram effect was lost, and it did clear up the difficulty of stones and birds entering the intake, icing up of intake, and the propeller root troubles. In addition, it lent help to boundary layer suction schemes if ever these came in.

AIR COMMODORE W. R. WORSTALL (Fighter Command). In the very early days of jets in Fighter Command they had had some trouble with the impellor in the Welland engine, and with the introduction of the Derwent there had been many failures of centre bearings. The centre bearing was quickly re-designed and it was now fair to say that the Derwent was giving little or no mechanical trouble.

It had been possible to reduce the establishment of fitters in squadrons equipped with Derwent engines to about half that required to service modern piston engines. This was an interesting point in favour of the jet engine.

He would not like it to be thought that no troubles of any sort were experienced. The most unreliable part of the engine was the fuel system. Failures of fuel pumps, barostats and throttle valves were still far too common. Fuel leaks were also a problem and he had heard it suggested that the reason they were the subject of complaint was that they were more noticeable than was the case with petrol leaks. He did not consider this to be true, as there seemed little doubt that paraffin had greater penetrative powers than petrol and it was most important that all fuel connections should be perfect. There had been many cases of broken fuel pipes, though it now seemed that the introduction of flexible pipes was improving this situation. Quite 90 per cent. of the servicing difficulties were associated with the fuel system and if these difficulties could be cleaned up there would be little work to be done by fitters.

The jet engine had brought other problems, the main one being the refuelling operation. It had been stated from time to time that almost anything could be burned in jet engines; indeed, the popular press had stated that they could burn coke ! The experience of Fighter Command was that it was necessary to filter the fuel far more carefully than petrol; it was also necessary to mix oil with the fuel, and this was a nuisance. Although one speaker had illustrated how economical a jet engine was for high speed flight, this did not alter the fact that a lot of fuel had to be put into the aircraft at frequent intervals. He hoped some serious effort would be made to help solve the refuelling problem. The high fuel consumption of pure jets had to be accepted and it was essential that re-designed filters and filler orifices be provided. It was

also necessary that a new type of refueller be developed with a pumping rate of at least 150 gallons per minute.

Another trouble experienced was that of starting the engines. A quick start was of vital importance to Fighter Command as the whole essence of operating a Fighter Command squadron was that it should be able to get into the air quickly. Up to the present time all jet engines had been started electrically and he was of the opinion that electrics always gave trouble and always would. The starting cycle of the Derwent was some 30 seconds; the average current throughout the starting cycle was some 300 amps, with a peak load of 600 amps. With the Goblin engine peak loads of the order of 1,000 amps were imposed. Such high currents quickly discharged starter trollies and the problems of re-charging accumulators and man-handling large starter trollies were serious. Various methods of providing the necessary starting current were at present being tried in Fighter Command and one of these was to rig up eight accumulators in a 15-cwt. van. Starting might be satisfactory at a civilian firm, such as the de Havilland Company, where only a few engines had to be started, but it was a different matter when two squadrons were located on one station and 24 starts had to be made at one time. Because of the real difficulties associated with starting jet engines in the Service he pleaded for some efficient methods of starting, and suggested a two-stroke piston engine, or a slow-burning cartridge, or anything else that was not electrical.

He agreed with Mr. Carter's remarks concerning the ease of servicing engines on the wing. This advantage was prejudiced in the Meteor as it took 45 minutes to undo the screws which held the engine cowlings.

A more efficient fuel contents gauge was more than ever necessary with pure jet engines. In his experience he had never seen a gauge in service which was entirely reliable.

Cabin heating and cabin pressurisation were most important for fighter aircraft which had to attain enormous heights within a couple of minutes or so. He had been interested to hear that the R.A.F. had a most efficient pressurised cabin. He had never met this cabin, and would be grateful if anyone could give him further details.

MR. E. M. BOSSON (Vokes, Ltd., Associate). The filtration industry was prepared to put out whatever filtration equipment was considered necessary for jet engines, provided that the jet engine people would state their exact requirements. The makers of the filtration equipment had not been able to get definite information, in spite of many attempts to do so.

MR. O. N. LAWRENCE (Joseph Lucas, Ltd., Associate Fellow). Air Commodore Worstall's remarks on the fuel system showed only one side of the picture. The only jet engines so far in use in the Service were the two earliest types, the Welland and the Derwent I.

The fuel system and control of gas turbines in aircraft presented new problems which had never previously been tackled so that systems entirely different from any existing ones had to be employed. There was little experience in the R.A.F. of the handling of this new fuel system. From the incorrect diagnosis of troubles and consequent unnecessary return of components, they were aware that further experience and instruction in the use of the system would enable the Service to reap greater benefits from the equipment supplied.

As the scope of work and numbers of these jet engines in the Service increased, the engine manufacturers and collaborating firms could modify or eliminate particular difficulties which arose in Service use; these troubles, in most cases, could not be detected by any other means than the mass testing which the fuel systems were getting in the Service.

To come more specifically to the points raised:—

(*a*) *Filtration and Inclusion of* 1 *per cent. oil in the fuel.*—They would note the omission of the prefix lubricating to the word oil, for that was not its purpose. It was required solely to combat corrosion. As mentioned before, the two engines under discussion had the earliest fuel systems on them. The Lubbock jets on the Welland used pistons, subject to fuel pressure on one side, opposed by a spring force. Further, both the Welland and Derwent I engines used barostats, a complex relief valve component again using sliding pistons opposed by springs; since both these sets of pistons were used for metering and control functions, it was essential that they remain absolutely free of "Stiction."

"Stiction" might be caused by foreign bodies silting up round these pistons, *i.e.*, they were acting as edge type filters, and filtering out the small bodies. Perhaps specks was a better word since trouble could arise from the most minute sizes.

Another potent source of "stiction" was any form of corrosion. Paraffin had a natural affinity for water and on various occasions large quantities of water had been found in the aircraft fuel tanks, perhaps collected there by condensation. Prolonged experience had shown that the addition of 1 per cent. oil reduced the corrosive effect of this water paraffin mixture to a great extent.

These were the reasons behind the provision of 1 per cent. oil and the extra fine filtration on these engines. They had long been convinced that the answer to these questions lay in the elimination of these lightly loaded sliding pistons. It was now two and a half years since the principles of a device to displace the barostat were put forward, which in conjunction with the departure from Lubbock jets removed all such pistons from the fuel system. Due to various circumstances, including changes in production requirements, these new components, B.P.Cs., could not be fitted to the earlier engines, although they had been available for more than 12 months. They were fitted to later marks of engines such as the Derwent V.

(*b*) *Leaks.*—These fuel systems when correctly fitted did not leak. Due to the high pressures that were necessary, it required some experience with the fuel system and skill to avoid leaks.

It was also worth remembering that paraffin evaporated slowly, and that leaks which were readily observed with paraffin would never be detected on a system using petrol because of the rapid evaporation.

(*c*) *Starting Systems.*—From their very nature, these engines required starter energies (*i.e.*, ampere hours) far in excess of conventional engines.

The original requirements were for reliable starts, and electric starting was the first system to be suggested. In the early days, the starting of Welland engines came in for considerable praise for reliability, etc. It was only after the aircraft were in the Service that complaints arose on the slowness of the starting.

He believed that the R.A.F. was producing engine-driven generators on the starter trolleys for other purposes; the use of these, by avoiding batteries, would obviate the present troubles.

DR. H. ROXBEE COX (Vice-President): He sympathised with Mr. Herriot's view that it was time they were able to make their pro-

totype aircraft more quickly. He had some sympathy with Mr. Petter's remarks but he felt nevertheless that they could, with advantage, take a lesson from what had been done on the other side of the Atlantic. The Shooting Star was a jet propelled gas turbine aeroplane, and the time which had elapsed from the beginning of the design to the first flight of the aeroplane was only 143 days. This was an example which they might well try to emulate.

He had understood Mr. Heron to suggest that the German jet engines were triumphs of aerodynamics and that the British were triumphs of metallurgy. The German engines, aerodynamically, were not so good as ours. Comparing the fuel consumptions of contemporary British and German operational engines, in the case of the British engines it was approximately 1.1 lb. per lb. thrust per hour, whereas that of the German engines was about 1.4 lb. per lb. thrust per hour. Further, the German engines were heavier and far less reliable than ours.

Mr. Aherne-Heron had expressed his belief in the cylindrical type of fuselage rather than the flying wing; and for the sort of speeds that Mr. Clarkson was discussing, no doubt that was the correct view. However, some of them still believed that the flying wing would come, even though their reasons might have changed since they had thought about it first ! If there were to be aeroplanes flying at supersonic speeds, they would necessarily have very curious shapes; they would be virtually low aspect ratio flying wings.

He could not criticise Mr. Clarkson's figures in any detail, but he believed that gas turbine economics were very dependent upon factors which they could not yet properly take into account. They would not know whether or not gas turbine engined aircraft were economical until they had flown them for a long time, one reason being that they did not know what people were prepared to pay for—for example—high speed. If they were prepared to pay for it, then such extra cost as might be involved in operation might be balanced. He felt, too, that in airline operation they would find that high speed was a virtue, not only in itself, but because it permitted higher frequency of service, and that might well be an important factor in the operational economics of the future.

Furthermore, much depended on the costs of fuels; those costs were to a considerable extent artificial, and would vary with the taxation ideas of the Government. They should not allow themselves to be too seriously influenced by paper arguments. Nothing could stop the gas turbine, and genuine economics would flow from operational experience.

In his review of the various types of civil aeroplanes, Mr. Clarkson had said that he was taking a jump from the smaller to the larger types, but, surprisingly, reference to the gas turbine mail aeroplane had been omitted. He thought that the type in which the gas turbine engine could best show its paces was the long-distance mailplane. It could operate at very high speed and a lot of space could be made available for fuel, because the amount of space necessary for crew and mail was relatively small. He asked for Mr. Clarkson's views on that.

There seemed to be a heresy in the remarks of a previous speaker who, in referring to engines on the wings, had seemed to imply that the increased rolling inertia would make some difference to the lateral control. It had been concluded some years ago that the increase of inertia in roll due to having engines on the wings did not have a material effect on rolling manœuvrability. Perhaps Mr. Carter would say if this conclusion had been modified ?

With regard to Mr. Carter's suggestion that it might be a good thing to provide rocket assistance for the take-off of a fighter, he pointed out that unfortunately the rocket would not be available to give any more assistance to the machine when in flight. The

best type of power plant would be one which would give extra thrust not only for take-off, but for climb and for combat as well when required.

This might be achieved (*a*) by fitting an "oversize" engine, or (*b*) by using a ducted fan type of power plant with afterburning behind the fan. With these alternatives the pilot could switch on extra thrust when he wanted it. He would like Mr. Carter's views on these suggestions.

They were apt to compare different types of engines as engines, whereas they could only really compare the virtues of the different types of engines by comparing also the aeroplanes in which they were to be installed. For example, the most interesting type of power plant which Dr. Ricardo had described *might* not be required for civil work if, as Mr. Clarkson had suggested, 5,000 miles range was enough; they might deal with that range more economically by using some lighter type of plant which used more fuel.

Therefore, in making comparisons of power plants from the point of view of overall economy—and Mr. Clarkson had not missed the point—they must consider what the aeroplane had to do and remember that the engine for maximum payload was not necessarily the one which used the least amount of fuel.

THE PRESIDENT. If there were a specification whereby everything was laid down and would not be altered for the next eighteen months or two years, it would be simple to make aircraft.

In that connection he recalled that at the beginning of October, 1917, his Company had been asked to make a four-engined machine of 30,000 lb. total weight, which was about twice the weight of any twin-engined machine then in operation. The new machine was flying by the end of March or the beginning of April, 1918, *i.e.*, after 6½ months. That was comparable with some of the jet figures! The reason was that at the beginning there was one conference to which everyone concerned was invited; after that, nobody was allowed to come near it from any official quarter whatever.

To-day the pure simple jet was delightful to look at, easy to install, to operate and to maintain. But they saw it gradually being contaminated by other things, having propellers fitted, having gears, having even to be compounded with Diesel engines or something else, and they looked at it in horror. Perhaps that was because they were unaccustomed to what would be necessary if the gas turbine were fully developed. When in retrospect, five years hence, they looked back at the simple jet engines of to-day, they might say, not how simple they were, but how crude. They had to become accustomed to a new type of engineering development, a new type of engine, and it might not be quite so simple as they would wish.

MR. H. DAVIES (M.A.P., Associate Fellow), *contributed*: It was a pity that in their attempts to demonstrate the ascendancy of the gas turbine so many speakers found it necessary to make claims which were open to doubt, because the well-established arguments in favour of jet propulsion in certain fields were so strong that they did not need such dubious reinforcing. Dr. Hooker made the claim that the low drag coefficient of the Meteor compared with the Spitfire was largely due to the absence of slipstream on the former. The difference in drag could be fully accounted for by the absence of cooling drag and improved general cleanness of the Meteor, and there was no reason for believing that the slipstream accounted for more than 2 or 3 per cent. of the drag at high speed of an aircraft like the Spitfire.

The statement by Dr. Hooker that the specific consumption of a jet engine became equal to the best achieved with reciprocating engines at a speed somewhere between 500 and 600 m.p.h. was of course true, but it

should not blind them to the fact that a jet aircraft cruising at these speeds would still need much more fuel to cover a given range with a given payload than a comparable orthodox aircraft cruising at, say, 350 m.p.h. Because fuel accounted for some 20—30 per cent. of the operating costs, the real problem was one of finding the best compromise between speed and economy.

With reference to the controversy about single and twin-engined fighters raised by Mr. Carter's paper; if they were considering the use of a *particular engine* there was no doubt that a twin-engined layout would have roughly a 50 per cent. better rate of climb than a comparable single-engined aircraft, with about the same top speed and endurance. But this would be at the expense of a considerable loss in manœuvrability because the twin would necessarily have either a larger wing area or a higher wing loading. If they accepted Dr. Hooker's statements about the time needed to develop jet engines, they would choose a much larger jet unit for a fuselage installation than for a wing-nacelle installation, and there was then no reason why the rate of climb of the single-engined layout should not be at least as good as the twin, and also have a higher top speed.

With regard to the axial versus centrifugal controversy, the main snag about the application of axial engines to twin nacelle aircraft appeared to be the difficulty of installing such engines with their thrust lines sufficiently near to the C.G. of the aircraft. It did not seem to be generally appreciated that fully underslung installations were unlikely to be acceptable because of the difficulty, particularly at low speed, of coping with the very large change in trim between engine on and off associated with the enormous thrust of these engines.

MR. F. RADCLIFFE (Handley Page, Ltd., Fellow), *contributed:* He had attended the complete session of gas turbine lectures and found the proceedings very comprehensive from the airframe designer's point of view.

The emphasis which was being given to the speed with which gas turbines could be designed and built could be very misleading. When a new type of aircraft was proposed, it was generally the case that there was not an ideally matched power unit available. It was either too big or too small. The natural reaction was to ask the engine designer to produce another model since it was such a relatively short-term job. Then they came up against realities. The engine firm was so busy that it had more in its programme than it could deal with, without taking on new commitments, and in any case tooling, etc., would not justify meeting the airframe designer's requirements for such a small number off—even though everyone realised that supremacy in aircraft design depended on just such a small detail as having the right power plant and not a makeshift compromise. The airframe designer was asked to take his unit off the aero-engine manufacturer's shelf. It was just as well, because the operator would be happier if he had well-tried engines in a new aeroplane.

It seemed to him that all that could reasonably be expected from the aero-engine firms would be a series of convenient powered units which were well proved, and then by the fullest co-operation of the power plant engineer and the airframe designer, the final product would be the best possible in the circumstances.

The remarks of Dr. Ricardo appeared to be pertinent, and pointed the way to what could be expected in the course of 5—10 years. All engines began as simply as possible, but development, competition and experience inevitably led to refinements which were often synonymous with complexity. It was interesting that the Americans had reported their progress with compound engines tested under conditions representing 30,000ft. at 2,000 r.p.m. with 40 in. intake manifold pressure.

In one arrangement a P. & W. 2,800 had geared to the crankshaft a standard turbo supercharger and gave .41 lb./b.h.p. hr. corresponding to a net brake thermal $\eta = .33$

In a second arrangement a P. & W. 2,800 had geared to the crankshaft a steady flow exhaust turbine and gave .34 lb./b.h.p. hr. corresponding to a net brake thermal $\eta = .40$.

In a third arrangement a P. & W. 2,800 had geared to the crankshaft a combination of a blow down turbine (a gas turbine with a Siamese stack arrangement and separate turbine nozzles for each cylinder) and a steady turbine in series. This gave .30 lb./b.h.p. hr. corresponding to a net brake thermal $\eta = .45$.

Although these were undoubtedly experimental, the results should indicate what could be expected in future power units for long-range transport aircraft.

He suspected rather that the present vogue for the centrifugal type of gas turbine resulted from the desire to exploit to the fullest extent the present experience with efficient superchargers for piston engines. This was natural, but it was unfortunate from the transport designer's viewpoint. The axial flow unit presented a much smaller frontal area than the corresponding centrifugal unit—1 : 1.78 in one case. This meant additional wetted area in a four-engined aircraft with four engines abreast. If, as Mr. Stafford had pointed out, the desire was to twin the units for reasons of offset moment reduction, in the event of an engine being dead, the axial flow was ideal, whereas the centrifugal arrangement was impracticable.

The axial flow gas turbine should be given much more attention than it was receiving at present. It appealed to him as the ideal layout for civil purposes, both for the reasons given above and also because with the higher compression ratios possible in the axial flow layout, a better fuel consumption could be expected.

THE REPLIES TO THE DISCUSSION

Dr. HOOKER

He had stated that Rolls-Royce, Ltd., had developed the Series V in three months, and had said that that feat would be repeated by many other jet engines in the future, and not only by engines made by Rolls-Royce. He did not mention this fact as an indication of the genius of the engineers engaged in developing jet engines, but merely to emphasise that, as turbine engines were developed, as each particular problem was solved, it was solved for all future turbine engines.

No engine was ever perfect, and always some modification could be made which would render it just a little better than formerly. The period of development which he had specifically described in his Fig. 2 was the period of time between the receipt of the first engine from the shop and the completion of an Air Ministry-observed type test. That seemed to be the logical period of development of an engine. The Air Ministry type test provided the seal that a sufficient standard of reliability for service in the R.A.F. had been achieved. In the case of the Derwent V engine, that was done in three months; and he ventured to prophesy that if the Company were asked for another centrifugal jet engine they could do it again. They could not guarantee at the same time a better fuel consumption, although they could provide more thrust per unit of frontal area.

Gas turbine engineers were not asking that all other machines should be thrown overboard and that all work should be sunk in the production of high altitude jet-propelled aircraft. They were merely asking for a fair share of the development potentialities of this country; they were not getting that fair share

from the aircraft side to-day. A machine that could replace the DC—3 could have jet propulsion; it could have a cruising speed of 400 m.p.h. and an ultimate range of 1,000 miles. That could be done, and must be done.

In his opinion the questions about economics, such as the cost per ton-mile, did not mean a thing. The prestige of the country in the air meant much more than the cost per ton-mile. All that they had to export was the product of their brains; they had to show that they were always leading, and they ought to do the job, as it could be done, immediately.

With regard to the reliability of the turbine engines, Air Commodore Worstall had said that he was able to reduce his fitting staff by half. That had been done in the first type of jet engine that had been put into service, and a design of which he was not unduly proud; there were better ones already. The Air Commodore had experienced troubles; but the kind of troubles that he had mentioned were noticed when there were no con. rods, main bearings, and so on, to fail ! In those circumstances one became pernickety, and was inclined to grumble if one could not get into a machine with an engine at O° C., press a button and take off straight away. That was an indication that the turbine engines were very good indeed, much better than the piston engines. He agreed that a 30-second starting period was not desirable, and assured Air Commodore Worstall that everything possible was being done to alter the starting arrangements.

On the question of the twin-engined versus the single-engined fighter, the function of a fighter aircraft was to take a man and some explosive or other weapons of destruction from point A to point B in the minimum time. It should be able to fly at the limiting mark number in all directions, except, perhaps, backwards ! It must climb quickly, and must have a thrust in it of a different order from that to which they were accustomed. The Meteor wanted 27,000 lb. of thrust, not 7,000 lb., and such engines were possible. He was not so much concerned as were some people about the frontal area of engines. He saw nothing wrong with the drag coefficient of the Meteor at 600 m.p.h. particularly, and he wished that Mr. Carter had shown a few more drag curves, perhaps relating to the Shooting Star or even the Vampire.

They could put two engines into a machine instead of one and increase the weight by only about 50 per cent. There was no law about it, but that was the proportion; 50 per cent. increase of weight for twice the engine power, with the corresponding improvement in performance.

There were lessons to be learned from the German engines. The use of low-grade materials by the Germans was excellent, and they would be well repaid by a study of the methods of cooling adopted by the Germans.

Mr. Seddon. There were three aspects of air intake efficiency to be considered:—

(1) The direct loss in ram pressure rise due to inefficiency.

(2) The effect of maldistribution of air upon the efficiency of the engine compressor, whether it be axial or centrifugal.

(3) The effect of the air intake upon the profile drag of the aircraft.

Mr. Seddon had mentioned the first two. He did not regard a loss of 20 per cent, of ram pressure as a very vital matter to the engine. The effect of the ram pressure on the engine was absolutely on a par with the effect of the forward facing intake upon the full throttle power produced by a piston engine. Twenty per cent. loss was thus small. The effect of maldistribution might be considerable and was likely to be far more serious in the case of axial compressors than centrifugals. The buffeting of the air on the first stages of the compressor might lead to mechanical vibration problems.

Now that the quantity of air consumed by the engine had become so great, in his view the effect of the air intake upon the profile drag of the machine must be examined carefully since, certainly at high speeds, this was liable to be by far the greatest loss.

Mr. Aherne-Heron. With all due respect to the German gas turbine engineers, or should he say aerodynamicists, they could not learn a lot by comparing the German engines with the British. Roughly, the comparison appeared to be that for a given thrust the German engines weighed almost twice as much, consumed about 30 per cent. more fuel and lasted about a quarter of the time of a Whittle type engine. They might argue that although it was admitted that the metallurgist had made the gas turbine possible in this country, the aerodynamicists just didn't make it possible in Germany. There were, however, a large number of detailed points on the German engine well worth studying for incorporation in future designs.

Might he remark that the German engines were axial flow engines!

Mr. W. E. W. Petter. He was in complete agreement with and would like to support strongly all Mr. Petter's remarks.

Air Commodore Worstall. Air Commodore Worstall had more experience of the serviceability and maintenance problems on jet propulsion units than any other man in the World. He should be cultivated assiduously by the Aircraft Industry, and then a few facts would come to light which might help to settle the worn-out argument of the reliability of jet versus piston engines. They knew that there was a great deal of cleaning up yet to be done on jet units, and he had no doubt that 10 years from now they would still be cleaning up jet engines. The perfecting of an engine type was never finished, and as the engine improved so the operator became more finicky.

They appreciated his remarks in regard to starting, and a great deal of work was now being done in this country on this problem.

Mr. H. Davies. He did not remember claiming that the low drag of the coefficient of the Meteor compared with the Spitfire was entirely due to the absence of a slipstream on the former. All he wished to state was the fact that the drag coefficient of the Meteor was only two-thirds that of the Spitfire, and he was not really bothered as to how this had been achieved, except to remark that it never had been achieved in the case of piston engine installations. He did not think he would get the radiator experts to agree that the cooling drag mounted to much, and in fact, they were all firmly convinced that the radiator actually pushed the aeroplane along for speeds of 400 m.p.h. and above.

Considering Mr. Davies's statement about fuel consumption in relation to speed, he did not think that even his 350 m.p.h. aeroplane would bear comparison with one travelling at 150 m.p.h., and no matter how speed was produced it was bound to be expensive. The question was, did they require speed in air transport or not? If not, he could not understand why people did not go by train. In fact, it had been said that the only thing that air transport had to sell was speed, and in all other respects every other form of transport was better — not excluding walking!

Mr. F. Radcliffe. When the profile drag of an aircraft got down to something like that appropriate to the skin friction on the wetted area then and not till then should they consider a centrifugal engine as undesirable for transport machines. He would remind Mr. Radcliffe of the facts, which were that the Meteor with nacelles on the wings had the lowest drag at high Mach numbers on any aeroplane so far calibrated. If transport aircraft could approach the Meteor then a great and tremendous step forward would be taken irrespective of the chimerical advantages of the axial unit.

In fact, a combination of centrifugal compressors was far better for the production of high compression ratios than the multi-stage axial because of the wider operating characteristics of the centrifugal stages. As his paper indicated, there was an optimum compression ratio depending on the rate in which efficiency of compression fell with compression ratio and with compressors available to them to-day this optimum was in the region of 6 or 7 : 1 compression ratio. It was significant perhaps that the jet engine with the highest compression ratio was of the axial type and yet its fuel consumption was not better than the centrifugal type. In fact, there were many features of design other than the compressor which contributed towards fuel consumption and with present knowledge, these fitted far better into the centrifugal arrangement.

Again, he would give the warning that pure thermal efficiency of the power plant was by no means the only important criterion. If it were, jet propulsion units would have no advantage against piston engines. The weight of the power plant alone in a new design was of vital importance, and here again the centrifugal unit had had the advantage throughout the development they had seen.

Mr. CLARKSON

Mr. Lee. After a lot of consideration on the basis of the analysis of the air liners it was decided that the best way in which to establish the facts was to take a constant size of aeroplane, which meant really a constant size of wing, and to apply to it varying amounts of power, in the appropriate ways.

The simple jet on the right-hand side of the diagrams must be operated at or near the ceiling; the jet wanted to go fast and the aeroplane wanted to be flown at maximum L/D, and one must try to bring the two together. The way to do that was to fly as high as possible. The more power that was put into the aeroplane, the higher it would go, and a point was reached at which it was bounded by Mach number as regards speed and power. Having done that, the take-off power was whatever it was.

An arbitrary bias was incorporated in the estimates to take account of the reduced CL max. of swept back wings where employed.

Fig. 6 dealt with "effective" cruising speed, whereas Fig. 5 dealt with simply the cruising speed or instantaneous cruising speed. The effective cruising speed was the cruising speed made good over a 2,200 mile run in still air after making alllowance for climb and descent and quarter of an hour for stand-off, taxying, etc.

Mr. Pearson. He was prepared to agree that his turbine engine was a great deal quieter than others. But did Mr. Pearson know why?

He had contested the statement in the paper that the take-off thrust of the simple jet was poor. The point was that in the case of transport machines for ranges of more than 3,000 miles, which had to carry big loads off the ground, the take-off thrust was poor "in relation to the cruising power or cruising thrust." That was the meaning of the statement in the paper. The cruising power or thrust necessary to do the job that had to be done was installed, and the aircraft was then found to be deficient in take-off thrust, in proportion to the cruising power, and compared with aircraft having propeller-driven engines.

Mr. Stafford. He agreed with his remarks about the offset thrust and the difficulties arising from the use of turbines. As they continued to put extravagant quantities of power into aeroplanes, as they could do with turbines — he did not mean wasteful quantities of power—they would get a crop of troubles associated with that, and a lot of "tunnelling" would be required to get them out. Slipstream effects, and so on, would tend to become more serious.

In the paper he was merely showing trends for coupling, and he was not vitally con-

cerned as to how the job was done. But there was a strong case for coupling the units, and he hoped the practical difficulties of coupling would not be too great. If from the aeroplane design point of view it was desirable to do that, they must face up to the problem.

Air Commodore Banks. He had expected to be criticised on the ground that the price of paraffin at 1s. 4d. per gallon was *high*; he had put it at two-thirds the price of petrol; but Air Commodore Banks had put it at 80 per cent. of the price of petrol. That seemed rather expensive, having regard to the relative current price and quality of the two fuels. Surely its price would be less than 80 per cent. of the price of petrol; at any rate, he thought it ought to be.

Mr. J. P. Herriot. The criticism, endorsed by other speakers, that the British aircraft manufacturer was not producing prototypes quickly enough, and the statement that the Americans were better in that respect, needed examination. The Shooting Star was designed, built and flown in 143 days; 138 days was 4½ months. The Mosquito, which was more than twice the job, was designed, built and flown in 10 months under conditions of black-out, A.R.P., dispersal, bombing, Battle of Britain, etc., etc.; and during this time two alternative models (fighter and turret fighter) were initiated and the programme repeatedly chopped and changed, and at the height of the Battle of Britain all Mosquito priorities were cancelled for a short time. No such condition of war emergency existed at Lockheed's during the design of the XP.80. It seemed, therefore, that in England they had nothing for which to reproach themselves by comparison with the American effort.

The pressure cabin was not a peculiarity of the jet aeroplane. All transport aeroplanes must cruise at 25,000 ft. in order to get over the weather, and therefore, they must have pressure cabins. He agreed that a tremendous amount of development lay ahead; but they had to face up to it, and he was glad to see that many people realised that.

Mr. Petter. He agreed fully with regard to the cross-over point as between the jet and the propeller efficiency, that other considerations were involved. The cross-over point might occur at 550 or 570 m.p.h.; but when one brought into the picture the weight and complication of the engine which was driving the propeller, the cross-over point came down to perhaps something like 500 m.p.h. or less. It was dangerous to consider just the propeller efficiency as the determining factor.

Mr. McOran Campbell. Fig. 8 was in order. The specific consumptions of the propeller driving turbine- and piston-engined aeroplanes considered in the figure were roughly of the same order, as were also their all-up weights and L/D ratios; it followed therefore that the slopes of their range-payload curves must be roughly similar.

Mr. E. J. Richards. In his analysis he had not found a strong case for the two-speed gear, in that, owing to the unsupercharged nature of the turbine, having installed the cruising power required, there was an abundance of take-off power available to meet the needs, even if the propeller converted it rather inefficiently into thrust. This was particularly the case with the higher cruising speeds and higher installed powers.

Air Commodore Worstall. One of the most interesting statements was that fitting staff could be halved as the result of using turbine engines. That was very significant They were getting some indication of the position in regard to engine maintenance, and it was useful to have definite evidence.

Dr. Roxbee Cox. The simple jet aeroplane in his picture was fairly representative of what the mailplane would be; the mailplane might be a little faster and a little more economical than the passenger aeroplane which he had considered. He could not see a very strong case for the pure mailplane.

There would always be a proportion of passengers who wished to travel as fast as the mails; furthermore, mixing of mails and passengers seemed to him to be a desirable thing from the operators' point of view. He agreed that they need not be discouraged by arguments put forward to show that gas turbines and high speed were uneconomical; he could not see that such arguments could possibly be substantiated by examination; the gas turbine offered cheap speed.

Mr. CARTER

With reference to the relative merit of the twin versus single jet, a thrust weight ratio of unity for the twin was about the best foreseeable at the present time. That ratio could be further improved by having engines on the wings, with one in the fuselage, and it might be necessary to consider an arrangement somewhat on those lines to get the utmost possible rates of climb out of the jet engine.

Dr. Roxbee Cox. It would be preferable to rely entirely upon the jet engine in order to avoid the complication of having dissimilar power plants with their different fuel requirements, but the curves showed how rapidly the rate of climb diminished with an unsuperchargeable engine, such as the gas turbine.

With rocket assistance a steady climbing rate could be maintained up to heights at which the aircraft was designed to operate on the jet installation. That was the outstanding problem of fighter design—to get to great heights in the shortest possible time.

Mr. H. Davies. He agreed that at first sight the single-engined machine was the more attractive proposition, but the question of balancing the aircraft might make it impracticable to put in a big enough engine to satisfy the future requirements of the Air Staff.

The relative position of thrust centre in relation to aircraft C.G. in order to avoid undesirable changes in trim would not, he thought, be among the major problems of designing fighters with axial flow engines on the wings. He agreed that this point would require careful consideration to arrive at the best all-round compromise.

THE PRESIDENT. The four papers and the discussion had been most inspiring and interesting; a great debt of gratitude was due to the authors of the papers and to all who had taken part in the discussion.

Everyone concerned would think hard about what the aeroplane would be like as the result of fitting jets. Mr. Stafford had raised the question of dealing with the offset thrust, now that thrusts would be so much better. It might be that the jet was so reliable and so easy to maintain that it was not necessary to have four-engined power plants, which were perhaps installed by reason of the unreliability of the piston engine; when the jet became still more reliable they might be satisfied with twin installations, even on very big aircraft.

The feature which had been interesting beyond anything else was the note of optimism on the part of everybody who had joined in the debate. There had been references to jet engines which could be made in very short time, and to aircraft which perhaps might be called, instead of Shooting Stars, Shooting Lines !

By such a meeting the Royal Aeronautical Society was fulfilling its very best purpose, that of stimulating interest in new developments connected with the science and engineering of aeronautics, and so raising the standard of technical achievement throughout the Industry and throughout the engineering professions connected with aviation. The large numbers attending was evidence of the great interest in the subject.

On the motion of the President, a hearty vote of thanks was accorded the authors of the four papers presented.

(Further contributions to the Gas Turbine Discussion will be published as correspondence in the June Journal.)

ROYAL AERONAUTICAL SOCIETY

WITH WHICH IS INCORPORATED THE INSTITUTION OF AERONAUTICAL ENGINEERS

ANNUAL REPORT OF THE COUNCIL
1945 — 1946

The end of the war with Germany in May, 1945, and with Japan in August, 1945, found the Society preparing to resume its peace-time activities.

A Membership Committee was appointed to review the whole field of membership of the Society and to put forward proposals for increasing the Society's activities. This Committee has now finished its report, and many recommendations have been made.

During the war two Committees, the Stressed Skin Data Sheets Committee and the Aerodynamics Data Sheets Committee, were appointed and issued a considerable number of sheets. These sheets came under the Official Secrets Act during the war, but are now being released and will shortly be available to all members who may want them. They proved of considerable value and were circulated during the war to official establishments, the industry, and to official quarters in Canada, Australia and the United States.

The Council have appointed a Technical Policy Committee to advise them upon the technical work of the Society. Two further technical committees were appointed during the year, one on Engines and one on Materials.

With the ending of the war it has been possible to resume fully the lectures programme. The considerably increased attendances at the lectures are, in themselves, a significant pointer to the increasing interest of members and others in the work of the Society.

On January 12th, 1946, the Society celebrated its Eightieth Anniversary. A dinner was held at the Guildhall on January 11th, 1946, and a Reception at No. 4, Hamilton Place, on January 12th, 1946. During the month many of the Branches took the opportunity to hold their own anniversary celebrations. The opportunity was taken to publish a history of the Society.

Council

PRESIDENT :

SIR FREDERICK HANDLEY PAGE, C.B.E., Fellow.

PAST PRESIDENTS :

SIR A. H. ROY FEDDEN, M.B.E., D.Sc., M.I.Mech.E., M.I.A.E., M.S.A.E., Fellow.
Mr. A. GOUGE, B.Sc., Fellow.
Mr. GRIFFITH BREWER, Hon. Fellow.

VICE-PRESIDENTS :

Dr. H. ROXBEE COX, Ph.D., D.I.C., B.Sc., Fellow.
Sir OLIVER SIMMONDS, M.A., Fellow.

Mr. E. J. N. ARCHBOLD, B.Sc., Graduate.
Air Commodore F. R. BANKS, C.B., O.B.E., M.I.Aut.E., F.I.P., M.S.A.E., M.I.Mech.E., Fellow.
Major G. P. BULMAN, C.B.E., B.Sc., Fellow.
Mr. S. CAMM, C.B.E., Fellow.
Mr. W. C. DEVEREUX, Fellow.
Mr. G. H. DOWTY, Fellow.
Mr. A. G. ELLIOTT, C.B.E., M.I.Aut.E., M.S.A.E., Fellow.
Mr. W. S. FARREN, C.B., M.B.E., M.A., F.R.S., M.I.Mech.E., Fellow.
Major F. B. HALFORD, M.S.A.E., Fellow.
Mr. P. G. MASEFIELD, M.A.(Eng.), Fellow.
Major R. H. MAYO, O.B.E., M.A., A.M.Inst.C.E., Fellow.
Mr. N. S. MUIR, B.Sc., Associate Fellow.
Mr. R. K. PIERSON, C.B.E., B.Sc., A.M.Inst.C.E., Fellow.
Major B. W. SHILSON, O.B.E., M.I.Mech., Fellow.
Captain C. F. UWINS, A.F.C., O.B.E., Fellow.
Mr. C. C. WALKER, A.M.Inst.C.E., Fellow.
Mr. B. N. WALLIS, C.B.E., F.R.S., B.Sc., R.D.I., M.Inst.C.E., Fellow.

Solicitor : Mr. LAWRENCE A. WINGFIELD, M.C., D.F.C., Associate.

Secretary : Captain J. LAURENCE PRITCHARD, Hon. M.I.Ae.S., Hon. Fellow.

Honorary Treasurer : Captain A. G. LAMPLUGH, Fellow.

Honorary Librarian : Mr. J. E. HODGSON, Hon. Fellow.

Committees of Council

Below are listed the various Committees of Council as constituted 1945.

Aerodynamics Committee
Mr. H. B. Irving (*Chairman*)
Mr. G. H. Lee
Mr. R. T. Youngman
Mr. H. F. Vessey
Mr. A. D. Young
Mr. R. M. Clarkson

Branches Committee
Major B. W. Shilson (*Chairman*)
Mr. E. J. Archbold
Mr. A. E. Russell
Mr. J. L. Batchelor
Mr. G. E. Petty

Education and Examinations Committee
Professor G. T. R. Hill (*Chairman*)
Dr. H. Roxbee Cox
Mr. W. S. Farren
Professor F. T. Hill
Mr. M. Langley
Mr. W. H. Cooper
Dr. N. A. V. Piercy
Air Commodore A. H. Robson

Finance Committee
Mr. W. C. Devereux
Captain A. G. Lamplugh (*Hon. Treasurer*)
Sir Frederick Handley Page
Major B. W. Shilson
Captain C. F. Uwins

Grading Committee
Lord Sempill (*Chairman*)
Mr. E. C. Gordon England
Professor F. T. Hill
Dr. H. C. Watts
Mr. R. S. Stafford
Mr. A. C. Clinton
Major G. P. Bulman

Journal Committee
Mr. G. H. Dowty (*Chairman*)
Major R. H. Mayo
Air Commodore F. R. Banks
Squadron Leader C. G. Burge
Dr. A. G. Pugsley
Mr. R. H. Sandifer
Mr. F. H. M. Lloyd
Mr. P. G. Masefield

Lectures and Debates Committee
Major G. P. Bulman (*Chairman*)
Mr. A. E. Russell
Mr. W. G. A. Perring
Air Commodore Helmore
Mr. B. N. Wallis
Mr. W. E. W. Petter
Major C. J. Stewart
Mr. F. M. Owner

Lecture Hall Committee
Professor L. Bairstow
Major B. W. Shilson

Lecture Hall Committee (*continued*)
Sir Roy Fedden
Mr. W. C. Devereux
Mr. A. Gouge
Colonel Abbott

Materials Committee
Dr. L. Aitchison (*Chairman*)
Mr. H. Grinsted
Dr. B. Chalmers
Mr. H. H. Gardner

Medals and Awards Committee
Mr. A. Gouge (*Chairman*)
Professor G. T. R. Hill
Sir Roy Fedden
Mr. W. S. Farren
Mr. W. G. A. Perring
Major C. J. Stewart
Dr. A. G. Pugsley

Membership Committee
Major B. W. Shilson (*Chairman*)
Dr. H. C. Watts
Mr. R. K. Pierson
Mr. E. J. N. Archbold
Mr. A. C. Clinton
Captain J. G. Hopcraft
Mr. A. G. Elliott

Rules Committee
Sir Oliver Simmonds (*Chairman*)
Major R. H. Mayo
Mr. L. A. Wingfield
Dr. H. Roxbee Cox
Mr. W. Tye

S.B.A.C. Liaison Committee
Sir A. H. Roy Fedden
Mr. A. Gouge
Major F. B. Halford
Sir Oliver Simmonds

Structures Committee
Dr. A. G. Pugsley (*Chairman*)
Mr. H. L. Cox
Mr. A. C. Brown
Dr. S. C. Redshaw
Mr. F. H. Pollicutt
Mr. H. R. Gillman
Dr. P. B. Walker
Mr. H. B. Howard

Technical Policy Committee
Sir A. H. Roy Fedden
Major R. H. Mayo
Mr. S. Camm
Dr. A. G. Pugsley
Mr. N. E. Rowe
Mr. A. Gouge
Dr. H. Roxbee Cox
Dr. L. Aitchison
Captain M. Luby
Mr. H. B. Irving

Representatives on Other Bodies

Advisory Committee for Aeronautical Engineering of the City and Guilds of London Institute : Professor F. T. Hill and Captain J. L. Pritchard.

Association of Special Libraries and Information Bureau : Mr. J. E. Hodgson (Honorary Librarian).

British Standards Institution Aircraft Committee : Sir Roy Fedden and Mr. A. Gouge.

British Standards Institution Jewels and Bearings Committee : Major B. W. Shilson.

Engineering Joint Council : Sir Roy Fedden.

Engineering Joint Council—Special Education Representative : Professor G. T. R. Hill.

National Central Library : Mr. J. E. Hodgson (Honorary Librarian).

Institution of Mechanical Engineers, National Certificates and Diplomas in Mechanical Engineering : Sir Roy Fedden and Professor F. T. Hill.

General Board of the National Physical Laboratory : Mr. W. C. Devereux and Mr. A. Gouge.

College of Aeronautics : Sir Roy Fedden and Dr. H. Roxbee Cox.

Membership

The Membership of the Society at the end of 1945 showed an increase over 1944 of 680 paid members.

During the war, the standards of the various technical grades were not lowered and it is expected that the large decrease in membership which followed the last war will not be repeated.

	Paid Members.		Life and Hon. Members.		Suspended.		Totals.	
Fellows	292	(267)	34	(27)	1	(1)	327	(295)
Associate Fellows ...	1517	(1370)	9	(8)	41	(13)	1567	(1391)
Associates	1551	(1033)	5	(5)	54	(13)	1610	(1051)
Graduates	568	(479)	—	(—)	36	(13)	604	(492)
Students	1136	(1225)	—	(—)	101	(36)	1237	(1261)
Founder Members ...	16	(15)	1	(1)	1	(0)	18	(16)
Companions	200	(211)	7	(9)	9	(5)	216	(225)
Temp. Hon. Members	—	(—)	35	(19)	—	(—)	35	(19)
Dec. 31st	5280	(4600)	91	(69)	243	(81)	5614	(4750)

NOTE.—Figures in brackets give the membership at December, 1944.

Annual General Meeting

The Annual General Meeting was held in the offices of the Society on Thursday, March 29th, 1945, at 5.30 p.m.

Present : Major B. W. Shilson (in the Chair)

E. J. N. Archbold (Graduate)
Griffith Brewer (Hon. Fellow)
A. C. Brown (Fellow)
Major G. P. Bulman (Fellow)
Dr. H. Roxbee Cox (Fellow)
P. L. Cronbach (Graduate)
Colonel H. Delacombe (Companion)
C. H. Elgie (Associate)
R. Goldby (Associate Fellow)
A. H. C. Greenwood (Associate)
J. V. Holman (Associate Fellow)
S. Scott-Hall (Associate Fellow)
Dr. D. M. A. Leggett (Associate Fellow)
P. G. Masefield (Associate Fellow)
O. Mayer (Associate Fellow)
Major R. H. Mayo (Fellow)
H. A. Mettam (Fellow)
L. A. Newman (Associate)
D. C. Smith (Associate Fellow)
F. O. Thornton (Associate Fellow)
L. A. Wingfield (Associate)

In attendance : The Secretary and Miss Barwood.

1. The Secretary read the Notice convening the meeting.

2. The adoption of the Annual Report was moved by Mr. Griffith Brewer and seconded by Major Shilson, and carried unanimously.

3. The meeting was then thrown open for general discussion by the members present. Major Shilson said there were quite a large number of people outside the Society who should be members and a Committee had been appointed to consider new membership. If members had any views on the subject the Committee would be glad to have them.

4. Mr. Scott-Hall said he thought that, although the new cover for the Journal was artistic, it was not the right cover for the Journal of a Royal Society.

   Major Shilson replied that it was important to get the views of members outside. If members would write in more it would help.

5. As a result of the Ballot it was announced that the following had been elected to fill the vacancies on the Council:—

Major G. P. Bulman	Major R. H. Mayo
Mr. S. Camm	Sir Frederick Handley Page
Dr H. Roxbee Cox	Sir Oliver Simmonds
Mr. W. S. Farren	Captain C. F. Uwins
Mr. P. G. Masefield	Mr. B. N. Wallis

6. The Secretary read the names of those proposed for Fellowship and passed by the Council.

Charles Francis Abell	Morien Bedford Morgan
Arthur Edward Bingham	Sydney Joseph Nightingale
Robert Boorman	Robert Bernard Cornelis Noorduyn
Duncan Cameron	Arthur Edgar Woodward-Nutt
Sir John Adrian Chamier	Edward Llewellyn Pickles
Herbert Eugene Chaplin	Douglas Rudolf Pobjoy
Richard M. Clarkson	Frederick Henry Pollicutt
Arnold Cadman Clinton	John Walker Ratcliffe
Eric William Densham	John Kerr Reid
Raymond Noel Dorey	Harold Rogerson
Bernard Arthur Duncan	Fred Rowarth
Alan Ferrier	Norman Rowbotham
Frederick Arthur Foord	Raymond Harold Sandifer
Sir Wilfrid Rhodes Freeman	Arthur Francis Scroggs
Henry Herbert Gardner	John Edward Serby
Charles Henry Griffiths	Beverley Strahan Shenstone
Stewart Scott-Hall	Joseph Smith
Arthur Stanley Hartshorn	Sir Ralph Sorley
Edward Dixie Keen	Kelvin Tallent Spencer
John Henry Larrard	Herbert Brian Squire
Philip Gadesdon Lucas	Reginald Spencer Stafford
Sir Francis K. McClean	Andrew Swan
Peter Gordon Masefield	Henry Beaumont Taylor
Albert Basil Miller	

7. Mr. L. A. Wingfield proposed that Messrs. Price Waterhouse be re-elected Auditors for the ensuing year for Aerial Science Limited and Aeronautical Trusts Limited. Mr. Scott-Hall seconded the proposals, which were passed unanimously.
8. Dr. Roxbee Cox moved a vote of thanks to Major Shilson for taking the Chair in the absence of the President.
9. Mr. L. A. Wingfield moved a vote of thanks to the Staff, which Major Shilson seconded.

The meeting terminated at 6 p.m.

Donations

The Council have to thank the Society of British Aircraft Constructors for the twenty-first year for their grant of £250 to the Funds of the Society.

The Endowment Fund in 1944 reached £119,820 19s. 6d. and this year the total is £131,775 15s. 9d.

The rapid growth of the Endowment Fund during the past seven years has largely been due to the many generous gifts from firms in the Industry and individuals. In the report of the Council for 1939-40 an account was given of the initiation of the Fund and its history, and acknowledgements were made in the Journal for October, 1939, of the seven-year gifts which were being received.

Large as the Fund may appear, however, a considerably greater sum will have to be obtained before the Society can own its own Lecture Hall, and it is hoped that all members will bear the Fund in mind.

President

Sir Frederick Handley Page, C.B.E., F.R.Ae.S., was elected President of the Society for the year October, 1945-September, 1946.

Vice-Presidents

The following were elected Vice-Presidents of the Society for the year 1945-1946:—

Dr. H. Roxbee Cox, Ph.D., D.I.C., B.Sc., F.R.Ae.S., and
Sir Oliver Simmonds, M.A., F.R.Ae.S.

Medals and Awards

During the year the Council made the award of the Gold Medal of the Society to Professor L. Bairstow. This is the highest award the Society can bestow.

The Elliott Memorial Prize and the Major Baden-Powell Memorial Prize were awarded as follows:—

Elliott Memorial Prize—S/A/A J. C. Ainsworth.
Baden-Powell Memorial Prize—W. Spence.

(Awarded to the best student in the May and December Associate Fellowship Examinations.)

Honours

The names of members receiving Honours during the year were published in the Journal for February, March and August.

Society of British Aircraft Constructors Scholarships

The Scholarship Selection Committee of the Society of British Aircraft Constructors and the Royal Aeronautical Society have made awards of Society of British Aircraft Constructors Scholarships to the following:—

September, 1945—*The John de Havilland Scholarship*—P. A. Hatswell.

The Amy Johnson Scholarship—Miss D. I. Gwynne.

Other Scholarships—R. F. C. Dleeker; P. L. E. Gallimore; A. M. Jackson; J. W. Headley; Miss J. E. Johnson; J. S. Moir; E. Rhoades; and F. J. Sealey.

Wilbur Wright Memorial Lecture

The Thirty-third Wilbur Wright Memorial Lecture was read by Mr. T. P. Wright, Hon. F.R.Ae.S., on "Aviation's Place in Civilisation" A full report of this lecture was published in the Journal of the Society for June, 1945.

British Commonwealth and Empire Lecture

The First British Commonwealth and Empire Lecture was read by Mr. W. Hudson Fysh, D.F.C., the Managing Director of Qantas Empire Airways on "Australia in Empire Air Transport." A full report of this lecture was published in the Journal of the Society for January, 1946.

Branches

The Council are glad to record that the Branches of the Society have maintained the considerable progress reported last year. During the year new branches have been formed at Leicester, Reading and New Zealand, while the Manchester Branch, which had been in abeyance during the war, resumed its activities. The number of members in the Branches now totals over 5,000.

The Society offered a prize for the best lecture read before the Branches by a member of the Society or of a Branch. The prize was awarded to Norman A. White (Graduate) for his lecture read before the Luton Branch of the Society.

Lectures

The following lectures were arranged during 1945:—

23rd January, 1945—Discussion on Civil Aviation.

15th February, 1945—Aircraft Wheels and Brakes, by Mr. J. Wright, A.F.R.Ae.S.

20th February, 1945—The Importance of Power Plant Development, by Air Commodore F. R. Banks, F.R.Ae.S.

1st March, 1945—Control Surface Design, Joint Lecture by Mr. M. B. Morgan, M.A., F.R.Ae.S., and Mr. H. H. B. M. Thomas, B.Sc., A.F.R.Ae.S.

8th March, 1945—Electrics for Aircraft, by Mr. C. G. A. Woodford, A.F.R.Ae.S.

13th March, 1945—Discussion on Civil Aviation.

22nd March, 1945—Hydraulics for Aircraft, by Mr. R. H. Bound, F.R.Ae.S.

5th April, 1945—Modern Experimental Work on Aeroplane Structures, by Dr. A. G. Pugsley, F.R.Ae.S.

4th October, 1945—The Future Scope of Propellers, by Mr. L. G. Fairhurst.

18th October, 1945—Aircraft Engine Oil Cooling, by Mr. F. Nixon, B.Sc., M.I.Aut.E., F.R.Ae.S.

1st November, 1945—A Critical Review of German Long-Range Rocket Development, by Mr. W. G. A. Perring, F.R.Ae.S.

15th November, 1945—(First British Empire Lecture.) Australia in Empire Air Transport, by Mr. W. Hudson Fysh, D.F.C.

27th November, 1945—Aspects of German Aeronautical Development, by Mr. W. J. Stern.

11th December, 1945—Meteorology and High Altitude Aviation, by Professor G. M. B. Dobson, F.R.S.

19th December, 1945—Atomic Disintegration, by Professor N. Feather, F.R.S.

Premium Awards

The Council have set aside an annual sum of £250 for the payment of premium awards to the authors of papers published in the Journal and it is hoped that members will be encouraged to submit to the Journal any papers they have written. A list of the 1945 awards was given in the April, 1946, Journal of the Society.

Graduates' and Students' Section

Ninth Annual Report of the Graduate and Student Section.

Summary.

The Section began its ninth session at the Annual General Meeting held at 4, Hamilton Place, on March 4th, 1946. During the year it has held ten technical meetings and has visited one works. The Section held its Annual Informal Dinner on the occasion of the Society's Eightieth Anniversary.

Committee.

During this session the affairs of the Section have been managed by a Committee consisting of the following:—

Mr. P. L. Cronbach, Graduate, Chairman.
Mr. R. T. Wall, Graduate, Vice-Chairman.
Mr. K. R. Obee, Graduate, Committee.
Mr. G. Roxburgh, Graduate, Committee.
Mr. R. L. E. Toms, Student, Committee.
Mr. J. Spillman, Student, Committee.
Mr. J. M. Hands, Student, Committee.
Mr. P. W. Wreford Bush, Student, Committee.
Mr. D. J. Hardy, Student, Committee.
Mr. E. J. N. Archbold, Graduate, Hon. Secretary.
Mr. J. W. F. Housego, Graduate, Ass't. Hon. Secretary.

The Committee accepted with regret the resignation of Mr. D. J. Hardy on his leaving the London area.

Technical Activities.

Since the beginning of the session the following technical meetings have been held:—

15th March, 1945—"Airworthiness," by Mr. W. Tye, A.F.R.Ae.S.

6th June, 1945—Impromptu Discussion.

25th October, 1945—"Production of Cold Rolled Sections for Aircraft," N. Aston, M.J.I.E.

6th November, 1945—" German Aeronautical Research," F/Lt. J. R. Ewans.
27th November, 1945—" Large Wooden Aircraft," J. K. Crowe, A.F.R.Ae.S.
7th December, 1945—Film show, " Steel " (Thomas Firth and John Brown, Ltd.).

In addition the Section was able to visit, on 12th August, 1945, the Cricklewood works of Handley Page, Ltd.

Annual Informal Dinner.

Sir Frederick Handley Page, C.B.E., the President of the Society, and Captain J. Laurence Pritchard were the guests of the Section at the Annual Informal Dinner held this year at Gunter's Restaurant on the Society's Eightieth Anniversary, Saturday, January 12th, 1946, following the Reception at Hamilton Place.

Work of the Committee.

In addition to the arrangement of the Section's technical activities the Committee met on two occasions to consider evidence to be laid before other Committees of the Society.

The Committee reported both to the Membership and to the Rules Committees of Council on aspects of their work affecting Graduates and Students.

Further, a meeting has been held, attended by Captain Pritchard and Mr. D. C. Smith, and also by Messrs. Deacon, Cooper and Collins, Apprentice Supervisors of Messrs. Handley Page, Ltd., Short Brothers and Fairey Aviation, Ltd., respectively, at which the attendance at Section technical meetings and the needs of the Graduates and Students generally were discussed.

Acknowledgements.

The Section wishes to record its indebtedness to Captain Pritchard for his continued active interest in and assistance to the Section, and also to Mr. D. C. Smith, the Assistant Secretary, for much practical assistance. The Section particularly wishes to thank Captain J. G. Hopcraft, of Thomas Firth and John Brown, Ltd., for the hospitality extended to the Section by that firm on the occasion of the showing of the film " Steel," and Professor G. T. R. Hill for kindly consenting to take the chair at the meeting of 26th February, 1946.

In conclusion, gratitude is due to those members of the Section who assisted in the visit to Messrs. Handley Page, Ltd., permission for which is acknowledged with thanks to the President, Sir Frederick Handley Page, and to those gentlemen who have prepared and read papers before the Section.

Associate Fellowship Examination

The results of the Associate Fellowship Examinations held in May and December, 1945, were published in the Journal for July, 1945, and March, 1946. There is again a marked increase in the numbers of candidates taking the examination, both in this country and various centres abroad.

Acknowledgements

The Council gratefully acknowledge the gifts of books, photographs, historical papers and lantern slides from members during the year. All gifts have been acknowledged as received, in the Monthly Notices of the Journal.

Honorary Fellowship

The Council elected Professor Leonard Bairstow, C.B.E., F.R.S., an Honorary Fellow of the Society in recognition of his work for the advancement of aerodynamics.

Honorary Companionship

The Council elected Mr. A. N. D. Smith an Honorary Companion of the Society in recognition of his work as Honorary Accountant of the Society for the past fifteen years.

Finance

The Income and Expenditure Accounts and Balance Sheets of Aerial Science, Ltd., and Aeronautical Trusts, Limited, for 1945 are published in the Journal with this report.

Journal

During the year a number of changes have been made in the Journal and an increasing number of articles published. Paper and labour shortage, however, have prevented an increase in size of the Journal and the improvements which have been under consideration.

The accounts show a considerable increase in the revenue over 1944, due to the unremitting efforts of Mr. G. H. Dowty, the Chairman of the Journal Committee.

Officers and Committees of the Society

The Council wish to place on record their appreciation of the work which has been done by the Honorary Officers of the Society during the year.

Captain A. G. Lamplugh, F.R.Ae.S., the Honorary Treasurer, has given invaluable advice and help on financial matters.

The Council particularly wish to place on record their appreciation of the work of Mr. A. N. D. Smith, who acted as Honorary Accountant for sixteen years. Mr. Smith's resignation during the year was accepted with great regret.

Mr. J. E. Hodgson, Honorary Librarian for so many years, has again during the year 1945 continued to advise the Society on all matters pertaining to the Library.

The Council also wish particularly to place on record their appreciation of the work of the various Committees. Much of the work being done by certain of the Committees has involved many meetings during the year and the results which they have achieved will prove of very great value to the Society.

Obituaries, 1945

*H. V. Becker (Student)
T. V. Broughton (Associate)
A. W. H. Dalrymple (Associate Fellow)
*F/O. J. A. Downie (Student)
P. D. Doxford (Student)
R. M. Lloyd (Associate Fellow)
C. F. Dendy-Marshall (Founder Member)
*C. W. Massey (Student)
D. Mooney (Companion)
*Sgt. P. M. Myers (Student)
Prof. H. Payne (Fellow)
Miss Agnes Baden-Powell (Hon. Companion)
Major J. C. Savage (Fellow)
Lt.-Col. Sir Francis C. Shelmerdine (Fellow)
M. H. Sheward (Student)
*Captain H. Snyder (Associate)
I. C. Swan (Graduate)
*W. H. M. Swann (Student)
*F/Lt. J. R. Talbot (Associate)
*Lt. L. Teff (Student)
Mrs. E. Tidswell (Hon. Companion)
A. N. Wallace (Associate)
*Lt. (E) A. W. Watson (Graduate)
O. Wels (Associate Fellow)
*E. A. Wright (Associate)

* Killed on flying duty.

THE ROYAL

(Aerial

Balance Sheet,

	£ s. d.	£ s. d.
Share Capital—		
Authorised—		
20 Shares of 1/- each	1 0 0	
999 Shares of £1 each	999 0 0	
	1000 0 0	
Issued—19 Shares of 1/- each, fully paid...		19 0
Sundry Creditors		4094 1 4
Subscriptions and Other Amounts Received in Advance		1858 1 9
Staff Pension Fund		4853 17 4
Publications Development Account		5183 16 0
Income and Expenditure Account—		
Balance at 31st December, 1944	2576 17 10	
Add—Surplus of Income over Expenditure for year to date ...	519 11 1	3096 8 11
		£19087 4 4

We report to the Members that we have examined the above Balance Sheet with the Books are of opinion that the Balance Sheet is properly drawn up so as to exhibit a true and correct information and the explanations given to us and as shown by the books of the Society.

3, Frederick's Place, Old Jewry, London, E.C.2.
13th March, 1946.

Income and Expenditure Account

	£ s. d.	£ s. d.	1944 Figures.
To Establishment Expenses—			
Ground Rent, Heating, Lighting and Insurance and Repairs, etc.		1654 10 11	(1479 11 7)
,, Office and Staff Expenses—			
Salaries	5279 2 11		(2795 14 1)
Printing and Stationery	1083 7 0		(765 18 7)
Postages and Telephone	752 0 3		(504 2 7)
Other Charges	970 16 8	8085 6 10	(1269 6 11)
			(5335 2 2)
,, Meetings		242 17 2	(183 13 6)
,, Library Expenses		574 9 0	(469 15 2)
,, Branch Expenses		128 11 6	——
,, Prizes and Donations		325 9 3	(5 5 0)
,, Dinners and Receptions		507 10 2	(Not shewn separately)
,, Legal and Professional Charges		278 5 0	(118 13 0)
,, Staff Pension Fund		1000 0 0	(1000 0 0)
,, Balance being Surplus of Income over Expenditure for year carried to Balance Sheet		519 11 1	
		£13316 10 11	

C. F. UWINS, Chairman, Finance Committee.
A. G. LAMPLUGH, Hon. Treasurer.

AERONAUTICAL SOCIETY

Science Limited)

31st December, 1945.

	£ s. d.	£ s. d.
Printed Books, Bindings, Old Prints, etc., at cost, less amounts written off		50 0 0
Stock of JOURNALS *and other Publications*		1 0 0
Investment in and amount due from Subsidiary Company—		
Aeronautical Trusts Limited—		
21 Shares of 1/- each, fully paid, at cost	1 1 0	
Amount due from Royal Aeronautical Society Endowment Fund	1539 2 2	1540 3 2
Staff Pension Fund—		
Investments at cost—£2335 10s. 7d. 2½ % Funding Loan, 1956/61	2201 4 2	
£550 0s. 0d. 3 % Savings Bonds, 1960/70	550 0 0	
£1050 3 % Savings Bonds, 1965/75 ...	1050 0 0	
	3801 4 2	
Cash at Bank	56 8 2	
Amount due from General Funds...	996 5 0	4853 17 4
Investment at Cost—		
£4000 0s. 0d. 3 % Savings Bonds, 1960/70	... ...	4000 0 0
Sundry Debtors	... ...	4009 12 6
Rent paid in advance	... ..	106 5 0
Cash at Bank and in Hand	... ...	4526 6 4
		£19087 4 4

of the Society, and have obtained all the information and explanations we have required. We view of the state of the Society's affairs as at 31st December, 1945, according to the best of our

(Signed) PRICE, WATERHOUSE & CO.

for the Year ending 31st December, 1945.

	£ s. d.	£ s. d.	£ s. d.
			1944 Figures
By Annual Subscriptions	... ...	10313 13 0	(8409 12 6)
,, Donation	... ...	250 0 0	(250 0 0)
,, Interest on Investment (*less* Tax)...	60 0 0		(60 0 0)
,, Income Tax Recovered	118 15 4		
,, Interest on Endowment Fund Investments (*less* expenses)	2448 1 5	2626 16 9	
,, JOURNAL and Sundry Publications—			
Sales	3187 15 10		(2081 3 1)
Advertisement Revenue	11366 14 4		(3064 19 3)
	14554 10 2		(5146 2 4)
Less—Printing Costs 6315 19 0			(4789 9 11)
Special Publications 500 0 0			(500 0 0)
Postages 586 5 6			(456 2 1)
Other Charges 1968 9 8	9370 14 2		(499 0 7)
	5183 16 0		(6244 12 7)
Less Amount transferred to Publications Development Account ...	5183 16 0	— — —	(Credit Balance 1098 10 3)
,, Examinations—			
Fees Received	481 17 6		(396 7 0)
Less Expenses	355 16 4	126 1 2	(326 7 1)
			(69 19 11)
			Excess of Expenditure over Income (900 18 3)
		£13316 10 11	

AERONAUTICAL

Balance Sheet,

	£ s. d.	£ s. d.	£ s. d.
Share Capital—			
Authorised—40 Shares of 1/- each		2 0 0	
Issued—21 Shares of 1/- each fully paid			1 1 0
Royal Aeronautical Society Endowment Fund—			
Capital Account—Balance at 31st December, 1944 ...		114021 2 3	
Add Donations received during year		8464 0 11	
Entrance Fees received during year		1507 13 0	
Profit on Sales of Investments		1983 2 4	
		125975 18 6	
Income Account—Accumulated Surplus at 31st December, 1944		5799 17 3	131775 15 9
Pilcher Memorial Fund—			
Capital Account—As at 31st December, 1944		99 14 0	
Income Account—Balance at 31st December, 1944 ...	51 10 4		
Add Income for year to date	4 0 8	55 11 0	155 5 0
Usborne Memorial Fund—			
Capital Account—As at 31st December, 1944		109 2 5	
Income Account—Balance at 31st December, 1944 ...	68 2 0		
Add—Income for year to date	3 19 0	72 1 0	181 3 5
Herbert Akroyd Stuart Fund—			
Capital Account—As at 31st December, 1944		688 19 0	
Income Account—Balance at 31st December, 1944 ...	394 17 5		
Add Income for year to date	31 8 0	426 5 5	1115 4 5
R.38 Memorial Fund—			
Capital Account—As at 31st December, 1944		978 3 10	
Income Account—Balance at 31st December, 1944 ...	661 0 11		
Add Income for year to date	47 3 10	708 4 9	1686 8 7
Edward Busk Memorial Fund—			
Capital Account—As at 31st December, 1944		449 6 1	
Income Account—Balance at 31st December, 1944 ...	180 11 11		
Add Income for year to date	19 14 0	200 5 11	649 12 0
Wilbur Wright Memorial Fund—			
Capital Account—Balance at 31st December, 1944 ...		1836 6 3	
Add Donations received during year		300 0 0	
Profit on Sales of Investments		11 8	
		2136 17 11	
Income Account—Balance at 31st December, 1944 ...	176 5 1		
Add Surplus of Income over Expenditure for year to date	13 14 1	189 19 2	2326 17 1
Simms Gold Medal Fund—			
Capital Account—As at 31st December, 1944		524 15 9	
Income Account—Balance at 31st December, 1944 ...	17 18 9		
Add—Income for year to date	15 0 0	32 18 9	557 14 6
Alston Memorial Fund—			
Capital Account—As at 31st December, 1944		245 6 0	
Income Account—Balance at 31st December, 1944 ...	30 6 1		
Add—Income for year to date	7 11 6	37 17 7	283 3 7
			£138732 5 4

We report to the Members of Aeronautical Trusts Limited, that we have examined the above explanations we have required. We are of opinion that the Balance Sheet is properly drawn up December, 1945, according to the best of our information and the explanations given to us and as

3, Frederick's Place, Old Jewry, London, E.C.2.
13th March, 1946.

TRUSTS LIMITED

31st December, 1945

	£ s. d.	£ s. d.	£ s. d.
Cash in Hand			1 1 0
Royal Aeronautical Society Endowment Fund—			
Leasehold Property at Cost—Less amounts written off			
4, 8, and 9, Hamilton Place		8730 0 0	
Furniture at cost, *less* depreciation		2885 12 6	
Investments at Cost —	£ s. d.		
£21081 19s. 1d. 3½ % Conversion Stock	21698 2 7		
£87235 12s. 5d. 3 % Savings Bonds, 1965/75	87801 17 4		
£1000 3 % Defence Bonds	1000 0 0		
£4100 L.N.E. Rly. 3 % Debenture Stock	3162 6 3		
£3100 L.M.S. Rly. 4 % Debenture Stock	3162 19 9	116825 5 9	
Cash at Bank		13284 15 5	
Amounts due for refund of Income Tax, etc. ...		4723 16 3	
		146449 9 11	
Less — Amount due to Aerial Science Limited ...	1539 2 2		
Amounts owing for purchase of Investments, etc.	13134 12 0	14673 14 2	131775 15 9
Pilcher Memorial Fund—			
£115 6s. 10d. 3½ % War Loan at cost		116 5 0	
Cash at Bank		39 0 0	155 5 0
Usborne Memorial Fund—			
£113 3½ % War Loan at cost		114 11 1	
Cash at Bank		66 12 4	181 3 5
Herbert Akroyd Stuart Fund—			
£683 1s. 0d. 3½ % War Loan at cost		698 19 0	
£250 3 % Defence Bonds at cost		250 0 0	
		948 19 0	
Cash at Bank		166 5 5	1115 4 5
R.38 Memorial Fund—			
£1048 11s. 2d. 3½ % War Loan at cost		1098 18 10	
£350 3 % Defence Bonds at cost		350 0 0	
		1448 18 10	
Cash at Bank		237 9 9	1686 8 7
Edward Busk Memorial Fund—			
£284 4s. 2d. 3½ % War Loan at cost		284 4 2	
£217 London Transport 4½ % "A" Stock, at cost		199 4 6	
		483 8 8	
Cash at Bank		161 5 10	
Amount due for refund of Income Tax		4 17 6	649 12 0
Wilbur Wright Memorial Fund—			
£1246 18s. 1d. 3½ % Conversion Stock, at cost		1000 0 0	
£1242 16s. 10d. 3 % Savings Bonds, 1965/75 at cost		1250 14 9	
		2250 14 9	
Cash at Bank		376 2 4	
		2626 17 1	
Less Amount owing for Purchase of Investments		300 0 0	2326 17 1
Simms Gold Medal Fund—			
£300 3% Defence Bonds, at cost		300 0 0	
£200 3 % Savings Bonds, 1960/70, at cost		200 0 0	
		500 0 0	
Cash at Bank		57 14 6	557 14 6
Alston Memorial Fund—			
£252 14s. 10d. 3 % War Loan 1955/59 at cost		250 0 0	
Cash at Bank		29 7 11	
Amount due for refund of Income Tax		3 15 8	283 3 7
			£138732 5 4

Balance Sheet with the books of the Company and have obtained all the information and so as to exhibit a true and correct view of the state of the Company's affairs as at 31st shown by the books of the Company.

(Signed) PRICE, WATERHOUSE & CO.

AERONAUTICAL

INCOME & EXPENDITURE ACCOUNTS

Royal Aeronautical Society

	£	s.	d.
To Legal Charges	4	4	0
,, Amortisation of Leasehold Property	485	0	0
,, Depreciation of Furniture	213	15	0
,, Surplus of Income over Expenditure for year transferred to Aerial Science Limited	2448	1	5
	£3151	0	5

Pilcher

To Income for year carried to Balance Sheet	4	0	8
	£4	0	8

Usborne

To Income for year carried to Balance Sheet	3	19	0
	£3	19	0

Herbert Akroyd

To Income for year carried to Balance Sheet	31	8	0
	£31	8	0

R.38

To Income for year carried to Balance Sheet	47	3	10
	£47	3	10

Edward Busk

To Income for year carried to Balance Sheet	19	14	0
	£19	14	0

Wilbur Wright

To 1945 Award	60	0	0
,, Surplus of Income over Expenditure for year carried to Balance Sheet	13	14	1
	£73	14	1

Simms Gold

To Income for year carried to Balance Sheet	15	0	0
	£15	0	0

Alston

To Income for year carried to Balance Sheet	7	11	6
	£7	11	6

TRUSTS LIMITED

FOR THE YEAR ENDED 31st DECEMBER, 1945.

Endowment Fund.

	£ s. d.
By Interest on Investments (gross)	2032 11 0
,, ,, ,, ,, (*less* Tax)	585 9 10
,, Refund of Income Tax	532 19 7
	£3151 0 5

Memorial Fund.

By Interest on Investments (gross)	4 0 8
	£4 0 8

Memorial Fund.

By Interest on Investments (gross)	3 19 0
	£3 19 0

Stuart Fund.

By Interest on Investments (gross)	31 8 0
	£31 8 0

Memorial Fund.

By Interest on Investments (gross)	47 3 10
	£47 3 10

Memorial Fund.

By Interest on Investments (gross)	9 18 10
,, ,, ,, ,, (*less* Tax)	4 17 8
,, Refund of Income Tax	4 17 6
	£19 14 0

Memorial Fund.

By Interest on Investments (gross)	73 14 1
	£73 14 1

Medal Fund.

By Interest on Investments (gross)	15 0 0
	£15 0 0

Memorial Fund.

By Interest on Investments (*less* Tax)	3 15 10
,, Refund of Income Tax	3 15 8
	£7 11 6

THE ROYAL AERONAUTICAL SOCIETY

Paper received March, 1946

BERYLLIUM, BERYLLIUM ALLOYS AND THE THEORETICAL PRINCIPLES AFFECTING ALLOY FORMATION WITH BERYLLIUM

by

G. V. RAYNOR, M.A., D.Phil.

Dr. Raynor holds the appointment of Research Fellow in Theoretical Metallurgy at Birmingham University. Formerly he was at the Inorganic Chemistry Laboratory at Oxford, where he worked for several years, partly in collaboration with Dr. W. Hume-Rothery, F.R.S.

BERYLLIUM, though of increasing application in the metallurgical and electrical industries, must still be classed as a relatively uncommon element. This would appear to be chiefly because no large scale application of the metal has yet been made; most commercial applications involve the addition of small amounts of beryllium to other metals, notably copper.

If a large scale use for beryllium were to be discovered, there would be little difficulty in the production of sufficient metal to fulfil a reasonable demand. Its ores are widespread, but unfortunately are seldom found in heavy local concentrations. The processing of these ores is somewhat difficult on a commercial scale, but not prohibitively so. Extensive researches have been made on these problems, because of the incentive given by the exceptional " lightness " of beryllium, its high melting point and particularly, by its high modulus of elasticity.

It is difficult to assess the question of the availability of beryllium ores. At the present time, the position in the British Empire appears to be that beryllium ore has come principally from the state of Ajmer-Merwara in India, to the amount of 98 tons in 1936. Sources of beryllium ore are to be found in Canada, and future production might well exceed this figure considerably (1).

The present production of beryllium is largely absorbed in the manufacture of copper-rich copper-beryllium alloys, which have excellent mechanical and electrical properties. Little application of, or exploration of, alloys rich in beryllium has been made. Beryllium-rich beryllium-aluminium alloys have been experimented with for certain purposes, but apart from this no advantage has been taken of the low density, high melting point, and the high Young's modulus of the metal. The reason for this is doubtless to be sought in the brittleness of such samples of beryllium as have been prepared.

It is felt that undue emphasis may have been placed upon this phenomenon of brittleness, and that in consequence investigation of beryllium-rich materials has been somewhat neglected. In the review which follows, the production and properties of beryllium are considered, and the possibility of producing beryllium-rich alloys for possible practical application is examined from the point of view of the general theory of alloy formation. Alloys in which beryllium forms a minor constituent are not considered, except in so far as they assist in understanding the factors operative when other elements are dissolved in beryllium. It is hoped that the review will indicate directions in which research might profitably be undertaken.

1. BERYLLIUM METAL.

The principal source of beryllium metal is the ore beryl, which has a constitution approximately represented by the formula $3BeO.\ Al_2O_3.\ 6SiO_2$, and a theoretical beryllium content of 5.0 per cent. Various processes exist for the extraction of the metal, all of which are somewhat similar in principle and take advantage of the solubility of beryllium hydroxide and carbonate in ammonium carbonate.

In a typical process, the ore is fused with potassium carbonate, and evaporated almost to dryness after the addition of sulphuric acid to the fused product. The residue from the evaporation is digested with water, and the silicous material, which is insoluble, is filtered off and rejected. Concentration and cooling of the filtrate leads to the crystallisation of a large proportion of the aluminium present as potash alum. The mother liquor is poured into a concentrated solution of ammonium carbonate, and the mixture allowed to stand. Iron and aluminium hydroxides are precipitated, but the hydroxide and carbonate of beryllium remain in solution. The filtrate from the hydroxides is boiled, and basic beryllium carbonate is precipitated. This may be ignited to beryllia BeO which, in essence, forms the starting point for the preparation of the metal.

Several chemical reactions are available for the preparation of beryllium from its compounds. It is not possible to reduce the oxide with carbon, although claims that some reaction takes place have appeared in the literature. If this be true, it is in marked contrast to the behaviour of the oxides of the other metals of Group IIA of the periodic table. It appears to be established, however, that when dry chlorine is passed over a heated mixture of beryllium oxide and charcoal, beryllium chloride $BeCl_2$ is formed. This compound is volatile and may be distilled into a suitable receiver. Its heat of formation is 112.5 k.cals/gm. mol., as compared with 153.2, 190.6, 195 and 197 k.cals/gm. mol. for the compounds $MgCl_2$, $CaCl_2$, 2(LiCl) and 2(NaCl) respectively. The chloride may thus be reduced by alkali and alkaline earth metals to form the metal, usually in the presence of hydrogen as an inert atmosphere.

In a similar manner the double fluorides with potassium or sodium, K_2BeF_4 or Na_2BeF_4, may be reduced with sodium or magnesium. The heat evolution is in all cases large, so that an inert atmosphere, or dilution of the reaction mixture with inert alkali or alkaline earth salts, is necessary.

Various attempts have been made to reduce beryllium oxide with metals such as aluminium or calcium, but these have not been very successful owing to the fact that the reactions are reversible and equilibrium mixtures are produced. Apart from problems raised by the choice of suitable refractories, these reduction processes are unsatisfactory because they give rise to metal which is in the form of powder, or small crystals, which contain much oxygen.

The most useful methods for the production of metallic beryllium are based upon the electrolysis of the fused anhydrous chloride, or of the double fluoride with an alkali metal, when beryllium separates at the cathode in either flakes or the massive form according to the temperature of the bath of fused salts. These methods, which are more fully discussed in Section II, are applied on a commercial scale.

There is, therefore, no lack of methods for producing beryllium of a reasonable purity. It is difficult, however, to effect the last stages of purification, so that many of the properties of beryllium referred to in the literature correspond to metal of purity of the order 98-99.5 per cent. This has caused some confusion with regard to physical properties, but the chemistry of the element is well established.

In the present review we shall not be greatly concerned with the general chemistry of beryllium. The chemistry of beryllium is similar, to a remarkable extent, to that of aluminium; the metal forms an excellent example of a non-typical first period element. There are several other examples of a first period element resembling the element in the following group of the second period, and there are sound theoretical reasons for these so-called " diagonal relationships " based on the pioneer work of Fajans. The diagonal relationships are of considerable importance in the theory of alloy formation.

Beryllium metal, like aluminium, oxidises superficially in air, and the oxide film is tenacious and protective. The metal has a high affinity for oxygen, and, when finely powdered, will burn in air; it does not decompose steam even at red heat. Beryllium reacts readily with many other gases, including nitrogen, but not with hydrogen, which may thus be used as a convenient inert atmosphere when the metal is heated.

The element forms many compounds, the properties of which are conditioned essentially by the very small ionic radius of beryllium. This factor leads to a tendency towards covalency formation in place of the ionic bond (*e.g.*, the formation of a volatile chloride which is non-ionised in the solid state) and to hydration of the ion in solution. The influence of the small size of the ion is of the first importance from the point of view of solid solution formation.

2. THE PRODUCTION OF BERYLLIUM OF HIGH PURITY.

In order to illustrate the problems involved in the production of pure beryllium, it will be of interest to consider in more detail the preparation of metal of technical purity, and its refinement. One of the early electrolytic processes, due to Lebeau (2), employed as electrolyte the fused sodium-beryllium double fluoride; fused beryllium fluoride is almost a non-conductor. The molten electrolyte was contained in a nickel crucible, forming the cathode, and graphite rods formed the anode. The beryllium, during electrolysis, separated as flakes in the fused mass and was subsequently recovered by wet processes. The metal flakes always contained oxygen.

The modern equivalent of the Lebeau process is the work of many investigators and has been largely developed by the Siemens-Halske A-G in Germany. The process employs a graphite crucible and a separate, water-cooled cathode, with an electrolyte of beryllium fluoride dissolved in fused barium fluoride. The electrolysis is carried out at a high temperature (1,250-1,300°C.), and by arranging for periodical raising of the cathode, irregular continuous bars of the metal may be produced.

At the anode, electrochemical attack takes place with the production of CO, CO_2, and CF_4. Because of this, any impurities in the graphite used are transferred to the electrolyte and ultimately to the cathode, thus reducing the purity of the metal produced. Graphite powder may also float on the surface of the melt, and contaminate the cathode material; beryllium reacts quite readily with carbon at high temperatures to form the carbide Be_2C. Thus the use of the purest graphite is essential.

The hot beryllium metal has also to be protected from atmospheric action; in practice sufficient protection is obtained by the solid skin of salts which forms in the neighbourhood of the cooled cathode.

When pure salts are used as starting materials, the purity of the final product is conditioned almost entirely by the quality of the graphite crucible. Beryllium of 99 per cent. purity may readily be produced by this process on a technical scale; with the better control

possible in laboratory experiments, metal of 99.7 per cent. purity may be obtained. A typical analysis of material obtained in a laboratory experiment is as follows (Sloman (3)).

Beryllium	99.7-99.8 per cent.
Iron	0.01 per cent.
Carbon	0.05 per cent.
Silicon	Trace
Aluminium	Trace
Nitrogen	0.005 per cent.
Oxygen as BeO	0.03 per cent.

It is doubtful whether metal of greater purity could be obtained by the process, a fuller description of which may be found in reference (4).

Another process which results in the production of metal of purity 99.8 per cent. relies on the electrolytic reduction of beryllium chloride fused with alkali chlorides. The process is essentially that of Borchers (5), and has been developed by the Beryllium Corporation of America and the Deutsche Gold und Silberscheideanstalt. The electrolysis is carried out at 730°C. in a steel container, using a tungsten cathode and a graphite anode. Contamination from the atmosphere is avoided by using an inert hydrogen atmosphere, which also prevents much of the attack on the graphite anode and thus reduces contamination from this source. The flakes of beryllium which are eventually separated have, however, a high moisture and oxygen content.

Massive metal is produced by forming the flakes into briquettes and remelting under an inert atmosphere (hydrogen and argon). One advantage of this method is the control which can be exercised on the purity of the beryllium chloride by pretreatment. Because of the differences in the boiling points of beryllium, aluminium, manganese, silicon, and iron chlorides, a simple fractional distillation may be used to give starting material of high purity. Several other processes have been developed, but those already given will suffice to illustrate the principles involved.

Further purification of the metal obtained is a matter of some difficulty, and the vacuum distillation techniques adopted by Sloman (3) and by Kroll (6) appear to be the only methods practicable. Even these have their limitations. The essentials of the process may be described by reference to the apparatus used by Kroll, whose technique was in some respects an improvement on that of Sloman. This apparatus is shown diagrammatically in Fig. 1.

The outer chamber is formed by a quartz tube, sealed at one end and closed at the top by a water-cooled metal stopper sealed on to it with vacuum wax. The use of metal avoids trouble due to gas evolution which always attends the use of rubber closures. Connection to the vacuum system is made by a ground metal joint sealed with vacuum grease. The beryllium is contained in a beryllia crucible, over which is placed a beryllia condensing hood to collect the metal distillate. This whole assembly is contained in a crucible of carborundum, and the free space between the beryllia, carborundum, and quartz vessels is packed with beryllia powder prepared by crushing the sintered material. Heat is supplied by means of a suitable high-frequency induction unit.

The charge of metal is first melted, under argon, without the condensing hood, and the temperature raised to 1,500°C. to expel moisture, salts, alkali metals and alkaline earth metals. After cooling to 1,000°C., the apparatus is opened, the hood placed in position and, after resealing, the whole apparatus is evacuated. The temperature is increased

gradually in order to expel gases from the apparatus and the metal (thus avoiding spitting) and distillation begins at approximately 1,300°C.

Distillation is normally done at 1,400°C., and the vacuum must be high. Unless the pressure is 0.001 mm. Hg. or less, higher temperatures must be used to avoid very slow distillation. The purity of the distillate depends on the duration of the distillation and the quantity of residue. Copper, iron, and silicon may distil to a limited extent if the operation is too prolonged. It is usual to distil two-thirds of the initial charge; the residue then contains much copper, iron, silicon, carbides, oxides and nitrides.

The boiling point of beryllium is lower than those of carbon and iron, and purification from these metals is relatively easy. Aluminium and manganese, however, have boiling points less far removed from that of beryllium. According to published data (7, 8) the vapour pressure of beryllium at a given temperature is higher than that of aluminium and lower than that of manganese.

In actual practice it is found that distillation makes little difference to the manganese

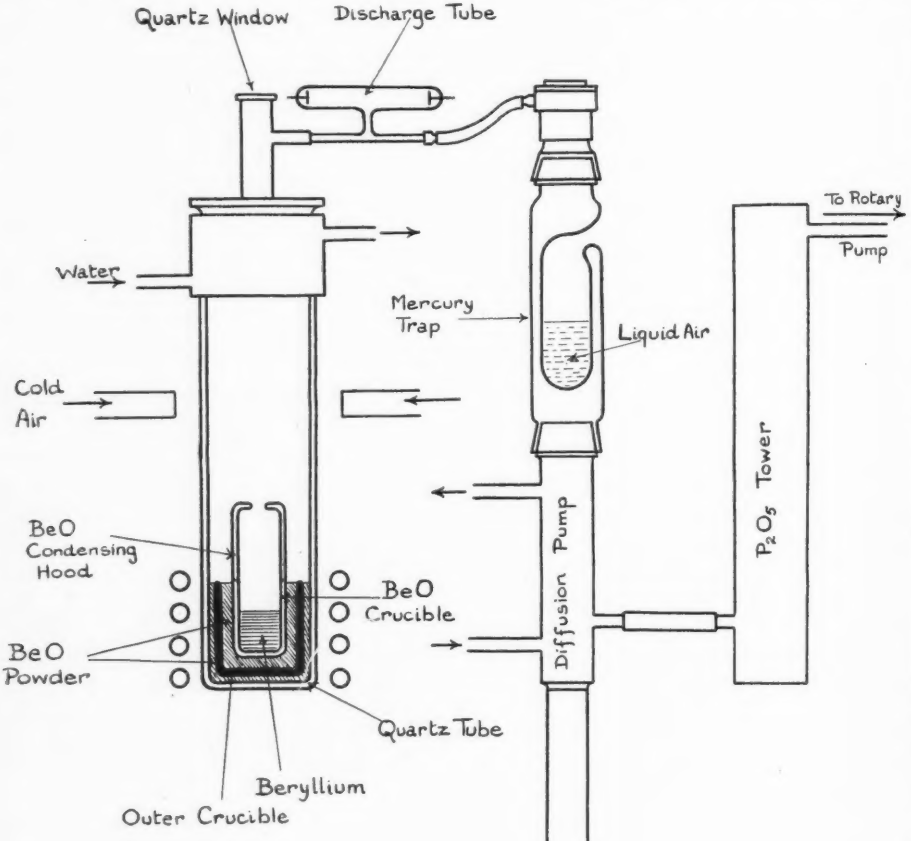


Fig. 1
Apparatus for the purification of Beryllium by Distillation.

content of the metal, while aluminium may even tend to concentrate in the distillate. The following figures, due to Kroll (9), illustrate this effect. The original sample was approximately 99 per cent. pure.

	Distillate 17 g.	Residue 23 g.
Aluminium	0.24 per cent.	0.11 per cent.
Silicon	0.036 ,, ,,	0.073 ,, ,,
Iron	Trace	2.08 ,, ,,
Manganese	0.38 ,, ,,	0.35 ,, ,,
Beryllium	99.344 ,, ,,	96.73 ,, ,,

It is probable that the reason for this behaviour is to be sought in the lowering of vapour pressure of components of alloys owing to stable compound formation; the evaporation of manganese can be almost stopped for instance, by the addition of carbon. Also, as in the simple case of alcohol and water, constant boiling mixtures may be formed, because of mutual interference of the various component metals. Since constant boiling mixtures distil unchanged, no further purification by distillation is possible once they have been formed. It seems likely that this effect is encountered in the distillation of beryllium, so that there is a limit to the degree to which purification can be carried out.

Starting with fairly pure metal, from which manganese should preferably be absent, it is possible to obtain samples of 99.97 per cent. purity by vacuum distillation.

3. THE PHYSICAL PROPERTIES OF BERYLLIUM.

Owing to the difficulty of purifying beryllium, physical properties quoted in the literature do not all refer to specimens of adequate purity, so that in some cases considerable confusion exists. In this section efforts have been made to choose only the most reliable values.

3.1. *Crystal Structure.*

It is now well established that beryllium has a crystal structure of the close-packed hexagonal type, but with an abnormally small axial ratio. The ideal close-packed structure and that of beryllium are shown in Fig. 2; the unit cell of the beryllium structure is also shown, the co-ordinates of the atoms being (000) (1/3, 2/3, 1/2). Many investigators have measured the lattice spacings of beryllium, with the following results:—

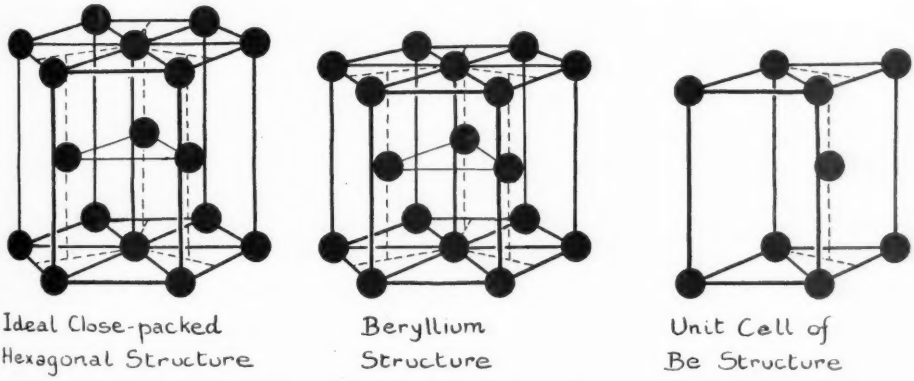


Fig. 2

Ideal close-packed hexagonal crystal structure, and the structure of Beryllium.

	a in A.	c in A.	c/a.
McKeehan (10)	2.283	3.61	
Jaeger and Zanstra (11)	2.283	3.64	
Owen and Pickup (12)	2.28105	3.57714	
Neuberger (13)	2.2680	3.5942	1.5847
Owen, Pickup and Roberts (14) ..	2.2812	3.5779	1.5685
Kossolapow and Trapesnikow (15) ..	2.2808	3.5735	
Owen and Richards (16)	2.2812		1.5682

It is a matter of some difficulty to interpret these results. Neuberger's figures, which are the lowest recorded, may be in error, or alternatively the other values may be false, owing to impurity. All the authors quoted state that their results apply to pure beryllium, but no figures for the oxygen contents are given. It is important to note that the Neuberger value was obtained using spectroscopically pure metal.

With regard to this problem, the work of Jaeger and Zanstra is of interest. They found that, after heating a beryllium sample to a high temperature, the specimen gave rise to new interference points in the diffraction pattern, which might be interpreted as due to the presence of impurity atoms in ordered positions in the crystal lattice, which was otherwise unchanged.

As beryllium and beryllium oxide contain the same metal ion, it is not unlikely that some solid solubility of oxygen in beryllium exists. The ordering, on heating, of these impurity atoms might well be responsible for the effects observed. In view of this, and because the introduction of oxygen into the beryllium lattice would be expected to give rise to a lattice expansion, it is probably best to choose the Neuberger value as characteristic of pure beryllium.

Using the Neuberger value it is seen that in metallic beryllium there are two sets of interatomic distances; each atom is surrounded by six other atoms at a distance of 2.2235 A and by a further group of six atoms at 2.2679 A. Goldschmidt (17), from empirical measurements of the lattice spacings of alloys containing beryllium in solid solution, has deduced an atomic diameter for beryllium of co-ordination number 12, of 2.25 A. For several reasons, which are beyond the scope of the present review, this figure is of more limited application than those derived from the crystal structure of the element.

There have been several suggestions in the literature that an allotropic modification of beryllium exists. No convincing evidence has yet been put forward, and little further reference will be made to this point.

3.2. *Density.*

The density of beryllium has been reported as between 1.816 and 1.844 g/cm.^{3} by various authors. In view of the difficulty of preparing good massive specimens of beryllium for experimental purposes, it is perhaps wisest to place most reliance on the value calculated from the X-ray measurements of Neuberger, namely, 1.857 gm/cm.^{3}.

3.3. *Coefficient of Thermal Expansion.*

The coefficient of thermal expansion of beryllium varies markedly with temperature. The linear coefficient of expansion has been quoted, for polycrystalline specimens, as 12.4×10^{-6} (18) and 13.3×10^{-6} (19) for the range 20-200°C. According to Hidnert and Sweeney (20), the coefficient has the value of 5×10^{-6} at -100°C. and 21×10^{-6} at 650°C.; the results of Losana (18) give values of 11.86×10^{-6} at 30°C. and 23.70×10^{-6} at 1,200°C.

Measurements of the thermal expansion by X-ray methods, which are in general satisfactorily consistent with those obtained with massive specimens, reveal a very marked anisotropy, as illustrated by the following figures:—

Owen and Richards (16)

T°C	50	100	200	300	400	500
$\delta\parallel \times 10^{-6}$	11.1	11.5	12.2	13.1	14.2	15.8
$\delta\perp \times 10^{-6}$	13.7	14.4	15.9	17.6	19.5	21.5

Kossolapow and Trapesnikow (15)

T°C	18-220°	18-320°	18-454°
$\delta\parallel \times 10^{-6}$	10.4	11.0	13.1
$\delta\perp \times 10^{-6}$	15.0	15.4	15.7

It is of interest to note that the linear coefficient at ordinary temperatures is close to that of iron.

3.4. *Melting Point and Boiling Point.*

The work of Oesterheld (21) on 99.5 per cent. pure metal gave a melting point value of 1,278°C ± 5°C., which is in reasonable agreement with later determinations, of which Losana's value of 1,284°C., obtained with metal of purity 99.96 per cent., is typical. The latent heat of fusion at this temperature is of the order of 275 cals/gm. (18).

Direct measurement of the boiling point is extremely difficult. According to Bauer and Brunner (7), however, who measured the variation of vapour pressure with temperature, the vapour pressure at any temperature may be expressed in the following form:—

$$\log p = -11{,}700/T + 6.5,$$ T being measured in °A.

From this formula, the boiling point at 760 mm. Hg. pressure is 3,240°A or 2,967°C. It is possible from vapour pressure measurements to derive a value for the latent heat of evaporation; calculation shows this to be of the order of 78,000 cals/mol.

3.5. *Specific Heat.*

The specific heat of beryllium is anomalous at ordinary temperatures; this fact, combined with the obvious similarity of beryllium to aluminium, led in early work to the assignment of a false valency of 3 to the metal. Measurements have been made at various temperatures, and the following figures recorded (Bauer and Brunner):—

T°A	71.40	79.50	97.5	208	282.5	377	463
Cp	0.153	0.213	0.351	2.44	3.60	4.68	5.34 cals/gm. mol.

3.6. *Conductivity for Heat.*

According to the work of Lewis (22), the thermal conductivity of beryllium varies from 0.232 cals/sec/cm²/cm/°C at −176°C. to 0.508 cals/sec/cm²/cm/°C. at 190.4°C. Thus it compares favourably with those of aluminium and magnesium.

3.7. *Electrical Properties.*

With regard to the electrical properties of beryllium, much confusion exists in the literature, because these properties in general are sensitive to the presence of small amounts of impurity. The work of Losana indicated that the electrical conductivity is 13.7 per cent. of that of copper at the same temperature. Sawyer and Kjellgren quote a value of the order of 40 per cent of the electrical conductivity of copper. It is probable that the latter value is the more nearly correct. It is possible that the true value may be found to be somewhat higher still with improvements in the production of sound specimens of pure metal.

3.8. *Speed of Sound.*

The high speed of sound in metallic beryllium may be of importance in certain possible applications. The most reliable determination of this value is 12,600 metre/sec. (19); the speed of sound in beryllium is thus about $2\frac{1}{2}$ times that in steel.

3.9. *Reflectivity.*

Beryllium surfaces will take a high polish which appears to be permanent, like that of aluminium. The reflectivity for white light reaches 55 per cent. (19). These facts, combined with the high value of Young's modulus and the low density, suggest optical uses for beryllium films.

4. THE MECHANICAL PROPERTIES OF BERYLLIUM.

Since very pure beryllium is in general obtainable only in small amounts, many of the investigations of the mechanical properties of beryllium have been made with impure metal. Some data are, however, available for metal of 99.5 per cent. purity.

Beryllium of high purity tends towards the formation of very large grains; some crystals in the free surface of furnace-cooled specimens may measure over an inch in diameter (19). Very rapid chilling is necessary to produce a reasonably fine grain size. According to the work of Sawyer and Kjellgren (19), a tensile test on a chill-cast bar turned down to a $\frac{3}{8}$in. screw-threaded specimen gave an ultimate tensile strength of 20,990 lb./sq. in. without measurable elongation. The hardness of this material, measured by the Brinell method (1,500 kg. load on a 10 mm. ball) was 114; the penetration, however, caused cracks, both inter- and intra-crystalline, to appear in the neighbourhood of the impression. The brittle behaviour of cast beryllium is illustrated by these facts and figures.

There appears to be no doubt, however, that beryllium of this purity (99.5 per cent.) can be hot-worked at temperatures of the order of 900°C.-1,000°C. In one such experiment (19) a $\frac{3}{4}$in. diameter cast bar was forged at 900°C.-1,000°C. into bar of about 0.36in. diameter; during this process the electrical conductivity rose to 42.4 per cent. of that of copper at the same temperature, as compared with a figure of 38.9 per cent. for the cast material.

The mechanical properties of this material, both in the " as-forged " condition and after annealing at 1,000°C. in hydrogen, are shown in the following table:—

	As Forged.	Annealed 1,000°C. in H_2
TENSILE TESTS.		
U.T.S. lb./sq. in.	29850	27000
Yield strength (0.2 per cent.) lb./sq. in. ..	—	26400
Proportional limit lb./sq. in.	9400	8700
Elongation on 4 diameters per cent. ..	0.0	0.0
Reduction of area per cent.	0.0	0.0
Modulus of elasticity lb./sq. in.	40×10^6	36.8×10^6
COMPRESSION TESTS.		
Yield strength (0.2 per cent.) lb./sq. in. ..	35300	—
Proportional limit lb./sq. in.	9200	—
Modulus of elasticity lb./sq. in.	42×10^6	—
Shear strength lb./sq. in.	38600	—
Density gm/cm.^{3}	1.844	—
Electrical conductivity (per cent. that of copper)	43.1	—

These figures illustrate the high value of Young's modulus, but also show that, in spite of the ability of the material to withstand forging at a high temperature, it behaves at ordinary temperatures as a brittle material. In this respect it is reminiscent of the behaviour of metallic bismuth.

There has been much discussion in the literature with regard to the brittleness of beryllium. In the pioneer work of Sloman (3) who examined metal of a very high purity, slip bands were frequently observed in the deformed material in the neighbourhood of hardness impressions. This was taken as evidence that pure beryllium should be ductile. The Brinell hardness numbers obtained by Sloman were markedly lower than those observed by later workers.

Whatever the properties of beryllium of 100 per cent. purity may be, it is certain that no one has yet succeeded in preparing beryllium, on a technical or semi-technical scale, with this desirable property of ductility.

It has, however, been established repeatedly that beryllium can be forged and rolled into sheet while hot (900°C.-1,000°C.). The rolling process is usually accompanied by cracking round the edges of the specimen, the cracks following well defined crystal boundaries. This is most marked during the early stages of reduction and the rolling becomes progressively easier as it proceeds (9). It has been suggested that, in order to facilitate the hot-rolling of the metal, the rolling blanks should be chilled rapidly during casting, so as to lead to as fine-grained a structure as possible. There would appear, therefore, to be no insurmountable difficulty in the hot-working of beryllium. The properties of the rolled sheet when cold are still poor, and the brittle behaviour is again shown. Cold brittleness appears therefore to be a characteristic of beryllium as normally produced.

The cold brittleness has been attributed to the presence of intergranular films of oxide or of Be/BeO eutectic material. The work of Sloman (3) showed that such an eutectic was formed at relatively low oxygen contents. It is difficult to believe that this can be the whole explanation, in so far as the flakes of metal obtained during the electrolysis of fused beryllium halides, which are almost certainly single crystals and therefore possess no grain boundaries, show no ductility either.

The possibility of solid solution of oxygen or other gases in beryllium is of course not ruled out; the presence of large oxygen atoms in the lattice might account for a very low ductility. In this case, the brittleness of the metal could be regarded as a function of the purity, and since methods for preparing beryllium of greater purity than that which can already be made in the laboratory would prove extremely difficult, it would appear that there is little hope in the near future of obtaining the metal with any degree of ductility.

The brittleness of beryllium may be due essentially to its crystal structure, though the experimental evidence so far available does not enable a definite statement to this effect to be made. The ductility of other commercial metals which crystallise in the close-packed hexagonal system suffers from the fact that in this crystal structure only the basal planes are available at ordinary temperatures for glide.

In zinc and cadmium these basal planes are planes of close-packing of atoms; in magnesium this is not strictly true, since the axial ratio of the magnesium structure is slightly less than the ideal value 1.633 for close-packed spheres. In the case of beryllium, with its very low axial ratio, the basal plane is not the plane of closest packing of atoms; since gliding tends to occur on the most densely populated planes, it is possible that the basal plane does not enter into the gliding process at ordinary temperatures. If this speculation is true, then no amount of purification would produce ductile beryllium.

If, however, alloying elements could be found which would sufficiently modify the crystal structure of beryllium to allow some simple plane to be concerned in glide, relatively ductile alloys might be produced. This possibility is examined later in this review.

It would be of great interest if the plastic deformation of pure beryllium, at all temperatures, could be studied so as to establish the exact planes on which the process occurred. This might be carried out by an orientation study of slip bands; so far as is known, no such research has yet been undertaken.

5. BERYLLIUM ALLOYS.

The only experimental alloys, rich in beryllium, which have been at all adequately studied belong to the Beryllium-Aluminium System. This system was probably chosen with a view to the production of ultra-light alloys having improved properties at high service temperatures (*e.g.*, for piston materials). Certain difficulties are present from the start.

The alloys, particularly at high beryllium contents, have an extremely wide range of solidification, which raises problems in casting technique. In addition, in order to cause alloying to occur, the melt has to be heated to temperatures very much higher than those which are usual for aluminium-bearing alloys, with the result that gases are readily absorbed and act as a source of all the technical troubles commonly associated with gases in metals. Although it is perfectly possible to produce beryllium-aluminium alloys on a semi-technical scale, it is not an easy matter at present to go much further beyond this.

It is generally accepted that alloys containing less than 70 per cent. of beryllium are workable and can be rolled. With greater beryllium contents the alloys become more and more difficult to handle. In addition, the properties of rolled material containing more than 70 per cent. beryllium again show cold-brittleness characteristics.

As an example of the properties of these alloys, the following figures are of interest. They were obtained by Johnson (23), using sand-cast test bars of the following composition:—

Be. 67.43 per cent. Al. 30.46 per cent. Si. 0.34 per cent. Cu. 0.12 per cent. Fe. 0.69 per cent. Mn. 0.90 per cent. Cr. 0.06 per cent. Tests were made at 20°C. and some at 260°C.

	20°C.	260°C.
Yield point (0.1 per cent.)	13600 lb./sq. in.	—
Proportional limit	3700 ,,	—
Tensile strength	13700 ,,	10480 lb./sq. in.
Elongation	Zero	1 per cent.
Brinell hardness	75	57
Density	2.05 gm./cm.^{3}	—
Modulus of elasticity	20×10^6 lb./sq. in.	—

Later work (19) using an alloy containing 28 per cent. of aluminium, the remainder being beryllium of 99.5 per cent. purity, showed an improvement on these properties; the material was tested in the chill-cast condition with the following results.

Tensile strength	25000 lb./sq. in.
Yield point	19000 ,,
Elongation	3.0 per cent.
Modulus of elasticity ..	29×10^6 lb./sq. in.
Brinell hardness	86
Density	2.03 gm./cm.^{3}

The endurance limit of this alloy (24) is given as 11,000 lb./sq. in. at 20×10^7 cycles.

Examinations of various wrought beryllium-aluminium alloys have shown that elongations of the order of 12-20 per cent. may be obtained when the beryllium content is below 40 per cent. Table I shows some of the results obtained. The conclusion is (24) that the strengths of the wrought binary alloys at a definite elongation are from 10,000 to 30,000 lb./sq. in. below those of many of the aluminium aircraft alloys, comparison being made at the same value of the elongation. Where ductility is important, the much higher modulus of elasticity of the beryllium alloys can hardly overcome this disadvantage.

The creep strength of the beryllium-aluminium alloys is said to be low. Even at the low stress of 5,000 lb./sq. in. binary beryllium-aluminium sheet may show over four times as much creep as duralumin alloy sheet at five times the stress. Creep resistance could probably be improved by additional alloying constituents.

The main advantage to be envisaged in the use of such alloys is their probable good behaviour at elevated temperatures. They would be unsuitable, however, for use above 644°C. owing to the fact that the eutectic formed between beryllium and aluminium melts at this temperature.

The working properties of the beryllium-aluminium alloys almost certainly depend upon the fact that the microstructure consists of beryllium grains surrounded by an intergranular network of eutectic material containing the ductile aluminium. Microstructures of this type are probably to be sought for in any exploration for other workable beryllium alloys, although it would be of obvious advantage to obtain alloys in which the beryllium or beryllium-rich grains were themselves ductile.

Some attention has been paid to beryllium-magnesium alloys, but because of the large difference in the boiling points of the two metals, only about 1 per cent. magnesium has ever been introduced.

It is possible that alloys of some practical use could be found by a more systematic investigation of solid solution formation in beryllium than has yet been made; the theoretical aspects of this are considered in the next two sections.

6. THE FACTORS AFFECTING SOLID SOLUTION FORMATION.

In this section a very brief résumé will be given of the factors which are likely to apply to solid solution formation in beryllium. Theoretical progress has not yet been sufficient to enable intermediate phase formation to be fully discussed in the case of beryllium. Thus attention is directed mainly to primary solid solutions.

In the first place, as shown by Hume-Rothery, Mabbot and Channel-Evans (25), solid solution formation is unlikely to take place to any extent if the interatomic distance of the solute constituent, measured as the closest distance of approach of the atoms in its crystal structure, differs by more than 15 per cent. of the interatomic distance, similarly defined, of the solvent constituent. This is a principle of very wide application and serves as a rough guide to the power of any metal to form wide ranges of solid solution.

Even when this " size-factor " is favourable, however, there are various other factors which tend to restrict solid solution formation. The two most important of these from the present point of view are:—

(*a*) The " relative valency factor." This expresses the fact that in general a metal of a given valency is much more likely to form solid solutions with a metal of higher valency than with one of lower valency. Solid solutions of metals of low valency in solvents of higher valency thus tend to be restricted.

TABLE I

Properties of Wrought AlBe Alloy (Al. Co. of America)

Be per cent.	Form.	Temper.	Tensile Strength lb./sq. in.	Yield Strength lb./sq. in.	Elongation per cent.	Hardness BHN.	Young's Modulus $\times 10^6$	Reduct. of Area.
9.8	Sheet	50% reduction	35500	33900	2.8			
9.8	Sheet	Quenched 562°C	22100	10300	25.5			
16	Sheet	50% reduction	39100	37200	2.0			
16	Sheet	Quenched 562°C	26400	12700	19.5			
19.94	Extruded	As-extruded	20800	10900	17.0	41	16.2	15.5
19.94	Extruded	Tested at 600°F	6620	4150	25.0		12.6	33.4
22	Forged	$\frac{3}{8}$ in. bar	28000	18000	4.5	62	20.0	10.5
22	Forged	$\frac{3}{8}$ in. bar	35000	20000	9.5	70		
23	Sheet	50% reduction	38000	35000	4.0	55		
23	Sheet	Annealed 300°C	26500	16900	12.5			
23	Sheet	Quenched 620°C	30200	18600	12.5			
23	Sheet	Quenched 620°C: Aged	33400	24300	12.0	54		
25	Sheet	75% reduction	53100	50750	2.8	81		14.55
25	Sheet	Annealed 750°C	39170	22450	14.3	65	13.85	
25	Sheet	Quenched 1115°F	38780	20250	18.7	65	16.95	
25	Sheet	Annealed 1115°F	33500	16250	18.3	59		
32.51	Sheet	50% reduction	52900	47900	2.0			
39	Sheet	75% reduction	58360	56150	0.5		19.5	
39	Sheet	Annealed 650°F	37920	33300	1.7			
39	Sheet	Annealed 775°F	39470	32900	2.0			
39	Sheet	75% reduction	62890	58450	1.5	94	18.3	
39	Sheet	Annealed 750°F	45860	33550	7.3	75	14.75	
39	Sheet	Quenched 1115°F	44630	27750	9.7	78	15.9	
39	Sheet	Annealed 1115°F	41460	23150	14.5	68		
40	Sheet 0.008 in.	As rolled	40000	31000	1.5		22.0	
40	Sheet 0.156 in.	Annealed	22000	13500	5.0			
67.5	Cast	Sand cast	13700	13600	0.0	75	20.4	
67.5	Cast	Tested 500°F	10480	—	1.0	57 (R.T.)		
70	Cast	Chill cast	25000	19000	3.0	86	29.0	

Sheet .064in. unless otherwise noted.

(*b*) The " electronegative valency factor," which expresses the tendency of primary solid solutions to be restricted when the components of the alloy form stable intermetallic compounds with each other.

In any given alloy system application of these principles will enable a guess to be made with regard to the form of the primary solid solubility regions. Other factors, important in particular cases, remain to be considered. Unfortunately the " size " of an atom cannot be described in terms of a single constant; the interatomic distances mentioned above provide a rough assessment of the conditions in a pure metal, but not necessarily of those in an alloy.

Metals and alloys consist of a regular array of positive ions, and can be regarded roughly as held together by the attraction between these positive ions and the valency electrons which belong to the structure as a whole. The important point is that the lattice points of the structure are occupied by ions. Each ion may be regarded as a cloud of negative electricity surrounding a positive nucleus, and the size of this cloud of negative electricity is of importance. Moreover, the distribution in space of the outermost parts of the ion cannot by any means be regarded as constant. It is capable of being deformed by the presence in its neighbourhood of other positive charges (**26**).

Therefore, in addition to the interatomic distances in the crystals of the elements, we have to consider the sizes of the ions and the capacity they may have for being deformed or for deforming other ions.

It then becomes possible to present a more general picture of the effect of size considerations in alloy formation. If the atomic diameters of the component metals of a binary system differ by much more than 15 per cent. and if their ionic sizes are comparable, the strain caused by the introduction of either on to the lattice of the other is too great for stable solid solution formation to occur. If, however, one of the metals has a small ionic diameter, it may be possible to introduce this constituent into the lattice of the other metal without too great a strain developing. Similarly, it may be possible to introduce a large ion on to the lattice of a metal which has a small ionic diameter, again without introducing too much strain. In addition, deformation effects may reinforce these tendencies.

This theory allows a reasonable interpretation of the fact that, in the alloys of copper with cadmium, indium, tin and antimony the solid solubility value approaches more and more closely to that required by electron theory principles as the atomic number of the solute rises, in spite of the fact that the size factor as estimated from the interatomic distances in the elements becomes progressively less and less favourable. This is because the size of the *ion* shrinks on passing from cadmium to antimony, thus allowing substitution to proceed more easily (**27**).

Ionic radii are usually established by measurement of the anion-cation distances in ionic crystals by X-ray methods. The measured distance is a function not only of the actual size of the ionic core, but also of the force with which the ions are held together. Ionic radii deduced from crystallographic data are therefore only strictly applicable to ionic compounds, in which ionic bonds are formed between oppositely charged ions.

In a metal, however, all the ions are positively charged cations and the electrons which, together with these cations would form neutral atoms, belong to the structure of the metal as a whole. There are no anion-cation linkages, and the radius of, for example, a Zn^{++} ion on the metallic lattice is not the same as that of a Zn^{++} ion in an ionic crystal, where it is attracted towards a divalent anion.

This difficulty may be overcome by using the so-called " univalent " ionic radii derived semi-empirically by Pauling (**28**, **29**). The list of radii obtained by Pauling was intended to give a series of values which should be independent of the force existing between ions, but which could be quickly corrected for the magnitude of this force.

The term " univalent " is unfortunate, but is retained because it has gained currency; by the univalent radius of a zinc ion is meant, not the ionic radius of a singly charged Zn^{+} ion, but the ionic radius which the doubly charged Zn^{++} ion would have in a structure in which the force between anions and cations was of the same value as that between singly charged univalent ions.

Later work on the ionic radii of ions of the inert gas type (*i.e.* ions whose electronic structure resembles that of the rare gases) was done by Zachariesen (**30**), who considered also the effect of co-ordination number on the interionic distances in salts. For this and other reasons Zachariesen's value, where available, is preferred.

The Pauling and Zachariesen ionic radii may be taken in alloy theory to give a measure of the size of an ion on the metal lattice (**29**). On this basis it is found that some metals, like copper, silver, and gold, have ionic radii not very much smaller than their atomic radii, while others, like the alkali and alkaline earth metals, have relatively small ions and a large amount of extra-ionic space in their structures. The former are termed " full " metals, and are relatively incompressible. The latter are termed " open " metals and have relatively high compressibilities.

From a consideration of ionic radii, therefore, we are able to modify and extend the application of the simple size factor rule, and, as outlined above, we may expect metals with small ions to be introduced rather more easily into a lattice than those with large ions. Conversely, if the solvent lattice is made up of small ions, introduction of larger ions may be facilitated.

At this stage it becomes important to consider the deforming powers and deformabilities of the ions. It is clear that, when two ions are side by side in a crystal lattice, the outer electrons of each ion are under the influence not only of their own nucleus, but of that of

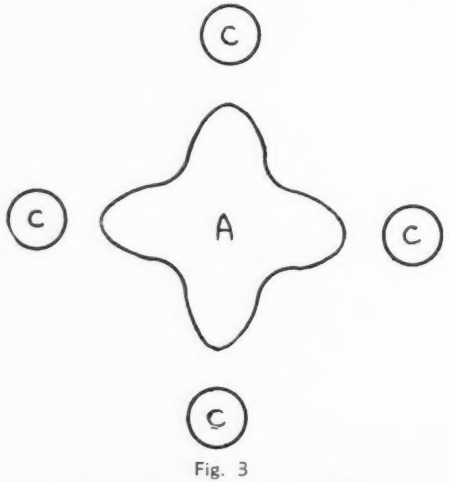


Fig. 3
Deformation of ionic ' atmosphere '.

the other ion also. In the classical case of a cation C and an anion A, the outer electrons of the anion are repelled by the negative charge on A, and are attracted by the positive charge on C. The ionic atmosphere of the anion is thus modified, as indicated pictorially in Fig. 3.

The effect, from the ordinary principles of electrostatics, will be greater the greater the radius and charge of the anion, and the smalle the radius and the greater the charge of the cation. Although the metallic lattice contains no anions, the same type of interaction may occur, enabling strongly deforming cations so to modify the electron cloud of introduced foreign ions as to enable them to adjust themselves more easily to their surroundings. Considerations of this nature have led (26) to the resolution of some difficulties which were incapable of interpretation on the simple size factor view.

It is necessary now to refer to the connection between the electron theories of metals and alloy formation. As is well known, Hume-Rothery (31) has worked out a series of empirical rules which relate the valency and the alloying behaviour of solute metals. These rules may be applied with considerable success to alloys in copper, silver and gold as solvents, and can be successfully interpreted in terms of the Brillouin Zone theory of metals.

A description of this theory would be beyond the scope of the present review, but it should be appreciated that, in a metal, the energies of the electrons cannot occupy a continuous range of energy values. There are energy gaps, the magnitude and position of which on the energy scale depend upon the particular crystal structure of the metal in question. It is not possible for electrons to possess energies within these energy gaps.

A further complication is that the energy values at which the energy gap begins and finishes are different for different directions in the crystal. This fact is not of great importance for the monovalent metals like copper and silver because the most energetic electrons present have energies far below the value at which the first energy gap begins.

By substituting for atoms of the solvent metal atoms of higher valency, electrons may be added to the copper and silver structures and this results in an increase in the energy of the most energetic electron present. This addition of electrons can continue until the energy of the most energetic electrons approaches the value at which the first energy gap begins.

At this stage further increase in the number of electrons per atom leads to a relatively sharp increase in the energy of the structure as a whole, which therefore becomes unstable with regard to other possible structures in which, by reason of their different crystal structure, the same number of electrons may be accommodated with a lower maximum energy. Considerations of this nature account for the well-known empirical rule that the solution of certain elements can take place in copper and silver until the electron : atom ratio reaches the value 1.4.

In the case of beryllium, which is a divalent metal, no such simple considerations apply. The form of the first band of allowed electronic energies for beryllium, with the close-packed hexagonal crystal structure, is such that it could just be filled in a structure possessing two electrons per atom, which is, of course, the number possessed by beryllium. In actual fact the situation is less simple, in so far as the lowest possible energy associated with the second band of allowed energies is lower than the highest possible energy associated with the first band of allowed energies.

The energies of the electrons are therefore distributed between the two energy bands; this is usually expressed by saying that " overlap " from the first band to the second band has taken place. The lower electrical conductivity of beryllium, as compared with that of

copper, is due to the fact that most of the electrons with energies lying in the first band cannot take part in the conductivity process. Only a relatively small proportion of them, together with all those with energies lying in the second band, contribute to the conductivity.

A further important consequence of an overlap of electrons from the first to the second band of allowed energies is that it may lead to a strain in the actual crystal (32). This strain is dependent upon the number of electrons per atom which have " overlapped," and can thus be varied by varying the number of overlapping electrons per atom.

7. APPLICATION OF THEORETICAL PRINCIPLES TO BERYLLIUM AND ITS ALLOYS

In the previous section several of the fundamental principles affecting solid solution formation have been discussed. These principles should be applied strictly with reference to the properties of the phase in equilibrium with the primary solid solution. As information with regard to these phases is lacking in the case of beryllium alloys, this factor will have to be ignored.

The simple size-factor rule gives a rough guide to the behaviour of binary alloy systems. It will be convenient to apply these considerations to beryllium in the first instance, and then to consider the modifying factors later. As explained in Section 3, the closest distance of approach of atoms in the crystal of the element is 2.2235 A. This value will be taken as characteristic of the beryllium atom; it is clearly more satisfactory to take this than the larger value of 2.2679 A, since the latter may refer to atoms not " in contact."

In Fig. 4 this closest distance of approach has been plotted, and horizontal lines have been drawn at values of 2.2235 A $\pm$ 15 per cent. The atomic diameters of the other metals have been plotted to the same scale, against atomic number. Some explanation of this diagram is necessary.

Although many of the metals have simple crystal structures with only one interatomic distance value (*i.e.* body-centred and face-centred cubic structures), others have less symmetrical structures in which there may be two or more distances of approach of the atoms. The single interatomic distances which arise from close-packed hexagonal structures of axial ratio other than 1.633 are given as full circles (smaller distance) and open circles (larger distance). Distances derived from less symmetrical structures are given as open circles joined by vertical lines. The point for manganese is provisionally plotted as 2.7 A because there is evidence from several sources that the manganese atom in solid solution may be of this effective diameter, whereas the interatomic distances in the crystal of the element are complicated and difficult to interpret.

This diagram shows at a glance that, because of the small atomic diameter of the metal, relatively few elements have a favourable size-factor with respect to beryllium. Only carbon has a smaller atomic diameter. The alkali metals, with the possible exception of lithium, have atomic diameters which are so different from that of beryllium that beryllium and the alkali metals would not be expected to be miscible even in the liquid state. In the case of lithium, immiscible liquids may not be formed, but no appreciable solid solubility of either metal in the other is at all likely. Similarly, no appreciable solid solubility of the alkaline earth metals in beryllium would be expected. In this connection it is of interest to note that there is no evidence for any solubility of beryllium in magnesium. Many of the other metals of the A & B sub-groups of the periodic table are also beyond the zone of favourable size factors with respect to beryllium.

Consider first those elements which fall entirely within the favourable zone. Of the A sub-group metals of the first period of the periodic table, only silicon has a favourable size factor. As we shall see later, other factors militate against any appreciable solid solution formation. The next group of metals to fall within the favourable zone is the transitional group comprising chromium, iron, cobalt and nickel, together with the univalent metal copper. Zinc, the next element to copper, is outside the favourable zone; gallium may possibly be considered as on the border-line, while germanium falls within the zone.

Elements of the other periods of the periodic table all lie outside the zone of favourable size factors. In the absence of any complicating factors, therefore, we might expect only silicon, chromium, iron, cobalt, nickel, copper and germanium to be worth considering as alloying elements.

Consideration of the ionic size of beryllium, however, indicates that the position is not as restricted as the simple view would lead us to expect. According to the univalent ionic radii published by Zachariesen, the ionic radius of beryllium is 0.55 A. Therefore there must be a large amount of " extra ionic space " in the structure of the metal, and beryllium falls into place as one of the open type of metals.

In Fig. 5 the atomic and ionic radii of several elements of importance to the present discussion are compared diagrammatically. The ionic radii are plotted vertically and the corresponding atomic radii horizontally. The dotted line at a slope of 45° from the origin represents ionic and atomic radii of equal magnitude. There are several points of interest

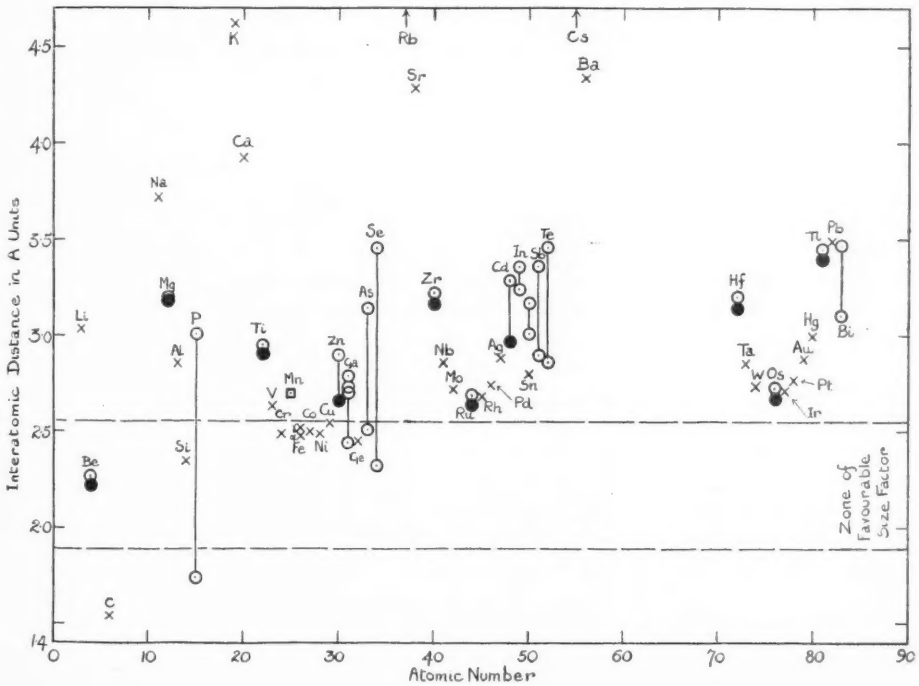


Fig. 4
The Interatomic Distances of the Metals.

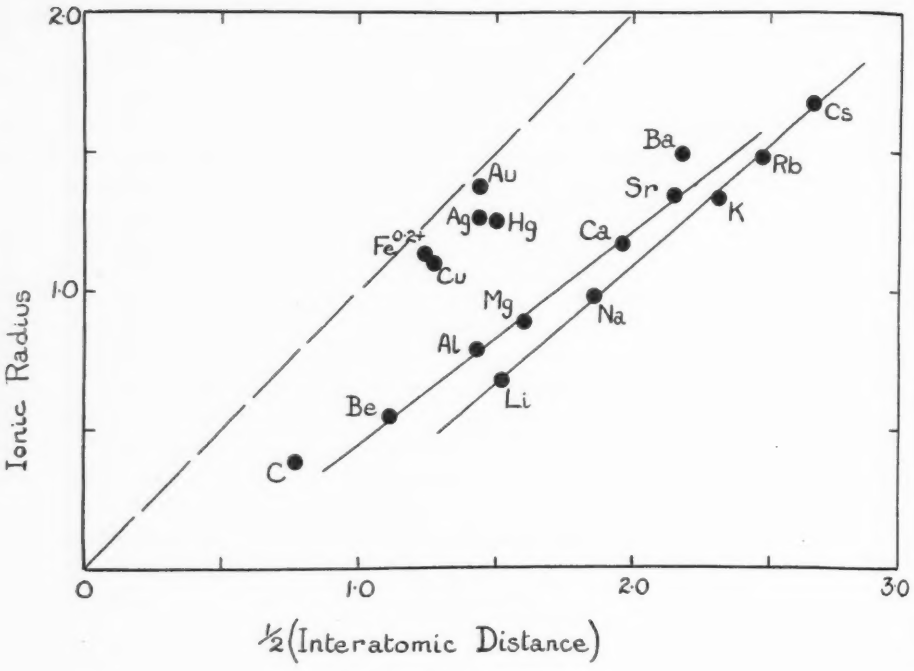


Fig. 5
Ionic radii plotted against atomic radii.

in this diagram; the points for the alkali metals lie on a single straight line which is well below the dotted line. This expresses the very open structure of these metals. The points for the alkaline earth metals and aluminium (with the exception of barium, which has a different co-ordination number from the other metals) lie on a similar straight line, which is also well below the dotted line. In contrast, the metals copper, silver and gold, give points much closer to the dotted line, indicating structures of a much more full type.

These metals, as mentioned above, have low compressibilities, because the structure may be regarded as built up of hard, incompressible ions in contact with each other. Data are scanty for the transitional metals; it is especially difficult to assign ionic radii to them, because, owing to the vacancies for electrons which exist in the outermost parts of their ionic shells, the true electronic state of the metal atom in the solid metal is usually not known. In the case of iron, however, the calculations of Mott and Jones (**33**) indicate that there are probably 0.2 effectively free electrons per atom in the solid state; the ions situated at the lattice points may thus be regarded as $Fe^{0\cdot2+}$ ions. A rough estimate of the radius of an ion of the type $Fe^{0\cdot2+}$ may be made by linear extrapolation from the empirical values for the Fe^{2+} and Fe^{3+} ions. When this point is plotted, it is seen that it represents a very full type of structure.

As far as they can be estimated, the transitional elements of the eighth group of the periodic table have all similarly full structures, as is reflected by their low compressibilities. The " extra-ionic space " of a few important atoms is:—

Element.	Vol. per atom A³.	Ionic Vol.A.³	Vex.
Li	21.6	1.317	20.3
Na.	39.7	3.942	35.76
K.	75.84	9.856	65.98
Be.	8.005	0.695	7.310
Mg.	23.08	2.95	20.13
Al.	16.5	2.065	14.435
Cu.	11.74	3.707	8.03
Ag.	16.95	8.3776	8.57
Au.	16.854	10.769	6.085

With such a large amount of extra-ionic space in metallic beryllium, it is quite possible that metals whose size-factors are definitely unfavourable on the simple view may yet be fitted into the beryllium lattice without the development of too much local strain. Support is given to this view by a consideration of the equilibrium diagram of the silver-beryllium alloys. This is shown in Fig. 6, and serves to give an idea of the magnitude of the effects involved.

In spite of the very large difference in the atomic diameters of silver and beryllium, silver will dissolve 3.5 atomic per cent. of beryllium, while beryllium will dissolve approximately 3 atomic per cent. of silver (34). This behaviour would at first sight seem even more remarkable in view of the tendency of a metal of lower valency to dissolve considerably more of an element of higher valency than the reverse. Such behaviour can be

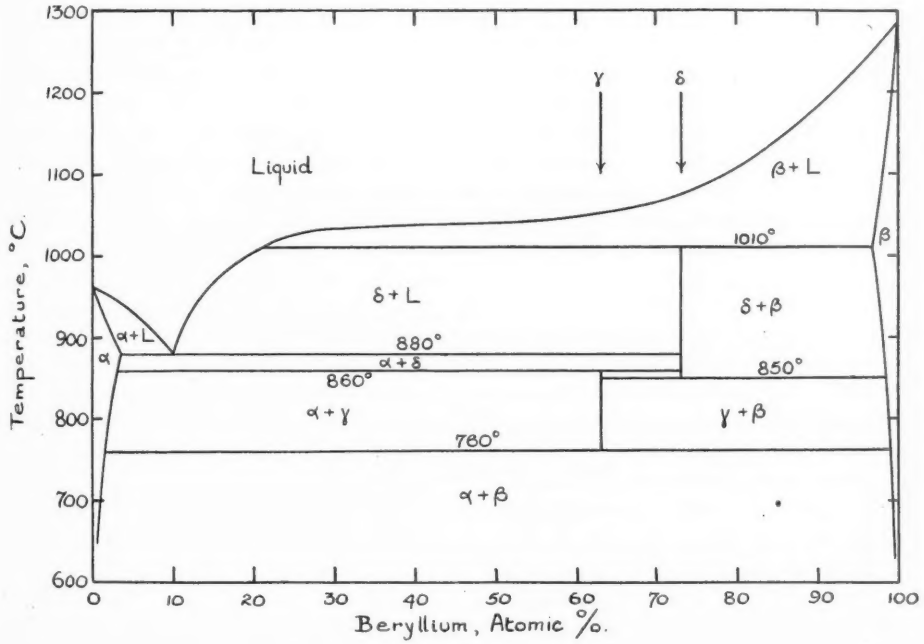


Fig. 6
Equilibrium diagram of the system Silver—Beryllium.

understood if, owing to the very small size of the beryllium ion, the silver ion may be regarded as being able to fit itself into the large amount of interionic space available.

In this connection, there is the ionic deformation effect to be considered. Beryllium, with a very small ion and two units of charge, is a strongly deforming ion. The larger silver ion is relatively deformable. The two may, therefore, interact so as to make the silver ion fit more easily on to the beryllium lattice. Expressed in another way, such interaction between the beryllium ion and the outermost parts of the silver ion may lead to polarisation forces of the Van der Waals type, which help to make the structure stable.

It is clear that, when considering solid solution formation in beryllium, the simple size-factor view of alloy formation is too restrictive. We must be prepared to take into account as possible alloying elements, not only those which have favourable size factors with respect to beryllium, but also those which lie considerably beyond this limit. Since we know that beryllium will dissolve 3.0 atomic per cent. of silver, we may fix an empirical upper limit for the atomic diameters of possible solute elements at 2.9 A. The following list of elements must therefore be considered —

Al, Si, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn ?? Ga, Ge, Nb, Ta, Mo, Ru, Rh, Pd, Ag, Sn, W, Os, Ir, Pt, Au.

Many of these elements are either precious or semi-precious metals of the transitional type. In view of their lack of availability, these will not be considered in detail; but the discussion of the transitional elements of the first long period will apply qualitatively to these metals also.

In Section 6 it was stated that solid solution formation was in general restricted by stable compound formation. This occurs when the components of the alloy are well separated in the electro-chemical series. Beryllium is a strongly electropositive metal, whereas the elements of Group IV of the periodic table, silicon, germanium, tin and lead, have an acidic character which decreases in the order given.

We might thus expect an intermetallic compound to be formed between beryllium and silicon, so that, even though the size factor is favourable, very little solid solution formation would be expected. Similar considerations apply to germanium. With tin, any compound formed would be of less stability, but since tin is approaching the border-line of our extended limit of size factors, little solid solubility, if any, would be expected.

Limited investigations of the systems beryllium-tin (35) and beryllium-silicon (36) have been made. In the former case, it is found that immiscible liquids are formed and that beryllium is only very slightly soluble in liquid tin; the solid solubility relations have not been adequately examined. In the case of the silicon alloys, Masing and Dahl have reported that the system is a simple eutectiferous one, with an eutectic at 61 per cent. Si and 1090°C., while the work of Sloman suggests that silicon is very sparingly soluble in beryllium. The absence of a stable intermetallic compound, if true, is somewhat remarkable, and from the theoretical point of view this system is worthy of re-examination. The atomic and ionic radii of lead are such that liquid immiscibility with beryllium would be expected.

We have seen that silver is soluble in beryllium. Gold has a similar atomic diameter and a similar ionic diameter to those of silver, and would be expected to dissolve to approximately the same extent. The ion of gold, however, is rather more deformable than that of silver, and this would tend to increase the solid solubility limit a little. Copper has a much more favourable size factor than either silver or gold, but the ion, being smaller,

is somewhat less deformable than the ions of silver or gold. These two factors oppose, so that we might expect a solid solubility of copper in beryllium of about the same magnitude as that of silver.

Theoretical principles, therefore, lead us to expect copper and gold to dissolve in beryllium to a limited extent of the order of 3.0 atomic per cent. In this connection it should be emphasised that these are univalent metals, whereas beryllium is divalent; the restrictions due to the relative valency effect therefore operate in such a way as to prevent the formation of any less restricted solid solution.

Similar considerations apply to the transitional elements of the first long period, except that a new restrictive factor may have to be considered. There is growing evidence that transitional metals in dilute solid solution have the capacity to absorb electrons from the structure into their own ionic cores. This produces two effects; in the first place they may act, in dilute solution, as metals of effectively negative valency, so that the relative valency restriction factor is reinforced; and secondly the absorption of electrons may alter the effective ionic radius of the transitional solute, leading to an increase in size. Although, therefore, Fig. 4 shows that the size-factors for chromium, iron, cobalt and nickel are more favourable than those for copper, silver and gold, it is probable that solid solution formation for these metals in beryllium is not markedly less restricted. We may expect a small solid solubility of these transitional metals in beryllium to take place.

Some support is given to this view by the fact that existing data show that both iron and nickel will take up appreciable quantities of beryllium into solid solution, so that, by analogy with the silver-beryllium system, a small range of solid solubility of these elements in beryllium is not fantastic. Nickel is capable of taking up 2.6 per cent of beryllium at 1155°C. while α-iron will dissolve as much as 7.8—8.0 per cent. of beryllium at 1150° C.

The conclusions we have reached for the transitional metals of the first long period as solutes probably apply in a general way to the two other families of transitional metals. Owing to the fact that in Fig. 4 these elements lie well outside the favourable size-factor zone, solid solution formation in beryllium would be expected to be more restricted than for the elements of the first long period. There are other reasons for believing this to be the case.

The elements titanium, vanadium, niobium, molybdenum, tantalum and tungsten remain to be considered. It is difficult to discuss these metals because little is yet known about their behaviour in solid solutions. If, as is probable, titanium acts as a 4-valent metal, and vanadium, tantalum and niobium act as 5-valent metals, the ions would not be expected to be very deformable. Titanium, tantalum and niobium would not be expected to be any more soluble in beryllium than aluminium is; vanadium, having a smaller atomic diameter might possibly dissolve to a limited extent. Molybdenum and tungsten may behave as 6-valent elements, or more probably like chromium. With the possible exceptions of molybdenum, tungsten and vanadium, it is doubtful whether any of these elements would dissolve to any appreciable extent in beryllium.

The general conclusion from this discussion, therefore, is that no common element has a wide range of solid solubility in beryllium. Only copper, silver, gold, chromium, iron, cobalt, nickel and the elements of group VIII in later periods are likely to form solid solutions in beryllium, and then only to a limited extent of the order of 3.0 per cent. by atoms. Vanadium, molybdenum and tungsten may be included in this group but the evidence is doubtful.

At this stage the electronic state of beryllium must be considered in rather more detail. It has already been said that overlap of electrons takes place from one energy band to another in metallic beryllium. This overlap concerns electrons which have energies in directions parallel to the basal planes of the crystal structure, and leads to what may be regarded as an internal strain in the crystal. Any reduction in this overlap (*i.e.*, the number of electrons whose energies lie in the second band of allowed energies) may give rise to a contraction of the lattice of beryllium in a direction perpendicular to the hexagonal axis, whereas any increase in the overlap would be expected to expand the lattice in this direction. In each case the " c " dimension of the unit cell would be expected to remain relatively unaffected. Such an effect is well established for magnesium (37), which also crystallises in the close-packed hexagonal system.

Now the solution of copper, silver or gold in beryllium effects a decrease in the number of overlapping electrons, because these metals have only one electron per atom as compared with the two electrons per atom of the beryllium for which they are substituted. In these cases the " a " axis of the crystal structure would be expected to shrink relatively to the " c " axis, leading to an increase in the axial ratio of the structure. It is not impossible that if the poor mechanical properties of beryllium are due to its crystal structure, these properties would improve with a change in axial ratio towards that of the normal close-packed hexagonal structure.

On the other hand, solution in beryllium of metals of higher valency would lead to a further decrease of the axial ratio, thus accentuating any abnormal properties due to the peculiar crystal structure.

The case of the transitional elements calls for special mention. Since it is probable that in dilute solid solution they act as absorbers of electrons from the structure, they will be much more effective than copper or silver in reducing the overlap of electrons in beryllium. Thus any solid solution of a transitional metal in beryllium would be expected to increase the axial ratio of the structure to a more marked extent than the corresponding amount of copper or silver. If axial ratio increases really do lead to improvement in the mechanical properties, these elements would effect a more marked improvement than others.

In the absence of experimental data it is not possible to discuss the extent of the axial ratio changes to be expected from the solution of approximately 3.0 per cent. by atoms of these elements in beryllium; but it is possible to say that chromium and iron might be expected to be more effective than cobalt and nickel. It is unfortunate that the restrictive effect of the relative valency factor on solid solution formation should be in the same order.

8. DISCUSSION

In the preceding section, by considering such factors as atomic and ionic sizes, deforming powers and deformabilities of ions, the relative and electronegative valency effects, and factors based upon the electronic structure of beryllium, we have come to the conclusion that beryllium should dissolve small amounts of copper, silver, gold, the transitional metals, and possibly vanadium, tungsten and molybdenum. The monovalent and transitional metals might be expected to lead to improvements in mechanical properties if sufficient could be introduced.

These conclusions are admittedly, and inevitably, speculative, but it is important to consider whether they lead to any hope of the development of useful beryllium alloys for practical purposes at ordinary and elevated temperatures.

At the outset it should be stated that it is not considered that the introduction of such small amounts of solute metals as 3.0 atomic per cent., which is the sort of solubility limit we are led to expect, would in themselves lead to sufficient change in axial ratio of the beryllium structure to make the solid solution ductile or workable at low temperatures. Such alloys when annealed should be workable at high temperatures and should retain strength in service at temperatures of the order of 700° C. It is probable that they would retain the brittle characteristics of beryllium at ordinary temperatures.

The question arises as to what characteristics might be expected if more of the solute element were added than corresponded with the solubility limit. These depend upon the form of the equilibrium diagram. It is known that many intermetallic compounds are formed between beryllium and other metals, even where no marked electrochemical attraction exists.

In the copper-beryllium system, in addition to the body-centred cubicphase, the phases CuBe (ordered body-centred cubic) and $CuBe_3$ (close-packed hexagonal) exist, the latter having a high melting point and a brittle nature. In the nickel-beryllium system, the compounds NiBe (melting at 1472° C) and Ni_5Be_{21} (melting at 1262° C) have been reported (38); the latter forms a eutectic with the beryllium-rich phase at 1240° C.

The compounds $FeBe_2$ and CoBe have been recognised; other beryllium compounds which have been observed are given below, with their crystal structures where known.

$AgBe_2$, $AuBe_2$, $TiBe_2$ } $MgCu_2$ type of structure

$CrBe_2$, $MnBe_2$, VBe_2, $MoBe_2$, WBe_2 } $MgZn_2$ type of structure

Pt_5Be_{21}—similar to Ni_5Be_{21}

Pd_3Be_4

$ZrBe_2$—deformed cubic structure

It is probable that in all the cases under consideration the phase in equilibrium with the beryllium-rich solid solution will be an intermetallic compound with a crystal structure of low symmetry and brittle characteristics. It is also probable that relatively high melting eutectics between the compound phase and the solid solution would exist. The cast microstructures of alloys containing the solute elements considered would be expected to contain intergranular eutectic material consisting of the beryllium-rich solid solution and a brittle compound. If the concentration of the solute element were less than that corresponding to the solubility limit this material could be absorbed by adequate annealing. If the concentration were higher than this limit, brittle intergranular material would persist, but would not necessarily be continuous.

In the case of all the solute elements discussed, the solubility in beryllium would be expected to decrease with falling temperature, thus raising the possibility of precipitation hardening to improve the strength characteristics of the alloys.

It seems clear that, in the case of the high melting elements discussed in the previous section, it would be unwise to hope for alloys with beryllium of very favourable mechanical properties. The alloys would be brittle, because of the characteristics of the beryllium grains and the material between them, and would not be expected to be capable of much improvement in this respect by heat treatment. On the other hand they would be hard and probably amenable to age-hardening, and would retain this hardness and strength up to relatively high temperatures. It is not impossible that such alloys could be of use as

castings, with or without heat treatment, in conditions where resistance to erosion or wear is important. Resistance to mechanical shock would be low, and elongation values also low.

The problem of producing ductile high-beryllium alloys does not seem to be approachable from the point of view of solid solution formation. The only means which at present appears possible for producing ductility is to develop alloys in which the beryllium grains are surrounded by a fair amount of material, eutectic or otherwise, which is itself ductile. Binary alloys for this purpose should therefore contain a ductile component and have equilibrium diagrams of such a form that a simple eutectiferous series is obtained.

The presence of stable intermediate phases, which would almost certainly be of a brittle nature, would prevent the inclusion of ductile material in the beryllium-rich alloys. Whether or not any solid solution took place in beryllium would be relatively unimportant in this case. These conditions are to some extent fulfilled by the beryllium-aluminium alloys, but not by the alloys with copper, silver, gold, and the transitional metals.

The disadvantage of using aluminium for this purpose is that the eutectic which is formed has a relatively low melting point of 644° C; such alloys could therefore not be used above this temperature. If the work of Masing and Dahl is correct, the beryllium-silicon alloys form a simple eutectiferous series with a high eutectic melting point of 1090° C. In this case, however, the eutectic material, containing both silicon and beryllium, would be very brittle, and no ductility could possibly result.

It would appear that for the production of beryllium alloys of some ductility only aluminium is worthy of consideration as an alloying element. The useful service temperature range is thereby limited. If, on the other hand, hardness and resistance to wear and abrasion are of more consequence than ductility, useful alloys for high temperature work might be developed by means of the other elements discussed above.

So far in this discussion only binary alloys have been considered. There remains the possibility of making up ternary or more complex alloys; in this case little can be said about the theoretical interpretation in the present state of our knowledge. From the outset, however, the prospect is not encouraging, at any rate from the point of view of developing ductility. The addition to beryllium of one or more high melting elements might lead to somewhat improved properties of the beryllium-rich solid solution grains; but the development of ductility, involving the addition of aluminium, would reintroduce the restriction to relatively low temperatures because of the almost certain formation of a relatively low melting complex eutectic. It is difficult at this stage to imagine improving on possible binary alloys by making further additions, except perhaps in order to improve creep characteristics.

As a result of this review, it seems clear that many problems connected with beryllium require further investigation. In the first place it is not yet clear whether the brittleness of " pure " beryllium is due to the small amounts of impurity, which are extremely difficult to remove, or whether the crystal structure is responsible. Further work on this problem would be of great value. Then, again, there is need for a systematic examination, using all the resources available to modern physical metallurgy, of the beryllium-rich regions of the equilibrium diagrams of several alloy systems, with particular reference to the solid solubility in beryllium.

Theoretical considerations suggest that the alloying elements which would most repay study are those of the first group of transitional metals, with copper and silver. If solid

solution formation is observed as suggested, then a systematic examination of the physical and mechanical properties of the alloys would be necessary.

It is possible that, by research of this nature, practically useful alloys of beryllium might be developed. Although the present review does not hold out any bright hopes of this achievement, it should help to focus attention on certain aspects which appear to be worthy of further attention.

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A NOTE ON THE USE OF PREFERRED NUMBER SERIES IN AIRCRAFT

by

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Mr. Conway took his degree, with honours, at Cambridge and served for three years with Petters, Ltd., before joining Rubery, Owen, Messier, Ltd. From 1939 *until* 1945 *he was Chief Engineer of Messier Equipment, Ltd., during which time he was responsible for all design and development, as well as Technical Sales and Service. He has extensive experience of undercarriages, tail wheel mechanisms and high-pressure hydraulic equipment. Mr. Conway is now Chief Engineer of the Dunlop Rim and Wheel Co., Ltd. He is a Fellow of the Society.*

1. INTRODUCTION

THE SO-CALLED Preferred or Standard Number Series is neither well-known nor often used in the British Aircraft Industry, perhaps because the series has not been published by the British Standards Institution or any other official body. Its use has much to commend it on the grounds of convenience and standardisation. Just as it is necessary for the international comprehension of science to standardise on basic symbols and terminology, so is it sometimes beneficial that numbers themselves should be widely used in the same manner.

The Series is published in France as the Renard Series, and also by the International Standards Association, using rounded off numbers to suit the metric system. The American Standards Association has published an American Standard differing from the I.S.A. table only in so far as certain values are rounded off to reasonable inch figures; included also is a table of more approximate fractional sizes.

2. APPLICATION

In laying out designs for a range of products, an engineer must inevitably be faced with the problem of deciding the size steps between successive units in the range. A simple example of this is in the range of household electric lamps, **15, 25, 40, 60, 100** watts.

A geometric progression is usually worth having so that the step from one unit to another can be of regular percentage increment; the Preferred Number Series standardises the numbers themselves so that similar numbers can be used for various separate solutions to a similar problem.

If the engineer goes a stage farther and uses a standard number for the size, rating, etc., of an apparently isolated design, he will be able to fit it into a standard range at a later date if larger or smaller units develop.

Examples of variables which can be standardised on Preferred Number lines are:—

—Important or characteristic dimensions, lengths, areas, volumes, capacities, weights, etc.

—Ratings in terms of horse power, kilowatts, voltages, currents (as on fuses), speeds, pressures, etc.

PREFERRED NUMBER SERIES

5 SERIES	10 SERIES	20 SERIES	40 SERIES	80 SERIES
10	10	10	10	10
				10·3
			10·6	10·6
				10·9
		11·2	11 2	11·2
				11·5
			11·8	11·8
				12·1
	12·5	12·5	12·5	12·5
				12·8
			13·2	13·2
				13·6
		14	14	14
				14·5
			15	15
				15·5
16	16	16	16	16
				16·5
			17	17
				17·5
		18	18	18
				18·5
			19	19
				19·5
	20	20	20	20
				20·6
			21·2	21·2
				21·8
		22·4	22·4	22·4
				23
			23·6	23·6
				24·3
25	25	25	25	25
				25·7
			26·5	26·5
				27·2
		28	28	28
				29
			30	30
				30·7
	31·5	31.5	31·5	31·5
				32·5
			33·5	33·5
				34·5
		35·5	35·5	35·5
				36·5
			37·5	37·5
				38·7
40	40	40	40	40
				41·2
			42·5	42·5
				43·7
		45	45	45
				46·2
			47·5	47·5
				48·7
	50	50	50	50
				51·5
			53	53
				54·5
		56	56	56
				58
			60	60
				61·5
63	63	63	63	63
				65
			67	67
				69
		71	71	71
				73
			75	75
				77·5
	80	80	80	80
				82·5
			85	85
				87·5
		90	90	90
				92·5
			95	95

It is obviously not possible to make all the dimensions of a product from standard numbers; for example, the diameter of a wheel may be standardised but the width may have to be some fixed percentage of the diameter for various reasons. If more than one factor of a range can be standardised so much the better, but the standardisation of the primary or characteristic variable is in itself an advantage.

The examples given in paragraph 4 below illustrate the advantages of the system better than any description.

3. DERIVATION OF SERIES

The Series consists of a number of geometric progressions based on the fifth, tenth, twentieth, fourtieth or eightieth root of 10. There are thus 5, 10, 20, 40, or 80 steps between 10 and 100.

The series is known as the 5-series, 10-series, etc. (or sometimes R5, R10 series, etc.). The 5-series, suitably rounded off is as follows: —

Step.	Derivation.	Exact Value.	Preferred Number.
0.			10
1.	$10 \times 10^{.2}$	10 x antilog .2 = 15.85	16
2.	$10 \times 10^{.4}$	10 x antilog .4 = 25.12	25
3.	$10 \times 10^{.6}$	10 x antilog .6 = 39.81	40
4.	$10 \times 10^{.8}$	10 x antilog .8 = 63.1	63
5.	10 x 10	10 x antilog 1 = 100	100

Table I gives the full decimal values as rounded off by the A.S.A. Standard.

4. EXAMPLES OF APPLICATION

Several interesting aicraft applications of this system serve to illustrate how it can be used with advantage.

(i) The Ministry of Supply and Aircraft Production decide to foster development of a range of electric actuators. The approximate limits of the range, in terms of operating load, are determined, and chosen from the shortest standard number series convenient.

The intermediate sizes are then given by this series or, if this is not extensive enough, by the next one. A typical range is shown in Table II.

Table II.

Number	1	2	3	4	5	6	7	8	9	10
Operating load, lb.,	160,	250,	400,	630,	1,000,	1,600,	2,500,	4,000,	6,300,	10,000

For the same and other applications, standard electric motors are designed. Instead of every motor designer producing his own ideas of motor rating, each uses standard numbers, thus creating the maximum degree of specification interchangeability. The range of motor power might be as in Table III.

Table III.

Number	1	2	3	4	5	6	7	8
Motor h.p.	.4	.5	.63	.8	1.0	1.25	1.6	2.0

(ii) Airscrew hub diameters might be selected from the 10-series:—

5.0, 6.3, 8.0 inches.

An intermediate size is required and the 20-series is used giving 5.6 and 7.1 inches. If still further sub-division is required, the 40-series is available.

(iii) Hydraulic jack and shock absorber diameters have been standaridsed by the Undercarriage Committee of the S.B.A.C. Unfortunately this was done without considerations of preferred numbers, and the range would be improved by alteration accordingly.

Table IV shows the present and standard ranges, the heavy type sizes being the main sizes and applicable to jacks only, the other sizes being for special use on shock absorbers when strictly necessary.

Table **IV.**

Present standard, in.,	**1.0**	1.1		**1.2**	1.25	**1.3**	1.4	**1.5**	1.6	
40-series, in.,	1.0	1.06	1.12	1.18	1.25	1.32	1.4	1.5	1.6	
Present standard, in.,	**1.75**		1.9	**2.0**	2.1	**2.3**		2.5	**2.6**	2.8
40-series, in.,	1.7	1.8	1.9	2.0	2.12	2.24	2.36	2.5	2.64	2.8
Present standard, in.,	**3.0**	3.25		**3.5**	3.7	**4.0**	4.25	**4.5**	4.8	
40-series, in.,	3.0	3.15	3.35	3.55	3.75	4.0	4.25	4.5	4.75	
Present standard, in.,		**5.2**	5.6	**6.0**	6.4					
40-series, in.,	5.0	5.3	5.6	6.0	6.3					

The advantages of this type of standardisation in giving component interchangeability between one maker of jacks and another, are obvious. It also has marked advantages from the point of view of the production of special tools, hones, tubes, etc., used in the manufacture of this type of equipment by all makers.

An interesting point is that the wartime Undercarriage Manufacturers Committee have standardised a range of piston rods associated with the above jack cylinder bore in arithmetic, not geometric progressions. This is because the main variable being the cylinder bore, the rod diameter is chosen for mechanical convenience only, and there is no particular significance in its size.

(iv) Although several firms make aircraft flexible hose for petrol, hydraulic fluid, etc., there is no standardisation of the lengths of hose involved. This leads to individual aircraft firms specifying their own.

Table V shows the Dunlop series of standard lengths.

Table V

Length of flexible hose (measured over ends) in inches.

Number	1	2	3	4	5	6	7	8	9	10	11	12	13
10-series (preferred use)	10		12.5		16		20		25		31.5		40
20-series (2nd preference)		11.2		14		18		22.4		28		35.5	

(v) A new range of hydraulic accumulators is to be produced and a convenient range of cubic inch capacities is formed by the 5-series.

10, 16, 25, 40, 63, 100 cubic inches.

(vi) Wheel and tyre standardisation is facilitated by the use of standard numbers. The dimension of rim diameters can be chosen from a standard series; the rim width can either be chosen from a standard series or, as has been done in some cases, the width is a fixed ratio of the rim diameter. Tyre diameters can also be standardised in the same way, as well as axle diameters subject to limitations in the availability of bearings.

5 SOME INTERESTING PROPERTIES OF THE SERIES

(1) The multiplication or division of two standard numbers gives a further standard number, subject to the inaccuracy introduced by rounding off.

(2) Since the factor 2.54 is nearly a standard number, a standard series in the metric system is approximately equivalent to a standard inch series when converted.

(3) Since " pi " (π) is practically a standard number, any series multiplied by it is still approximately a standard series.

(4) Since the cube root of 2 is approximately equal to the tenth root of 10, every third step of the 10-series gives the convenient series, 10, 20, 40, 80, 160, etc.

THE SOCIETY'S AWARDS

The Society offers a number of valuable awards, most of them annually. Full particulars of the conditions attaching to these awards may be obtained on application to the Secretary.

Society's Gold Medal

This is the highest honour which the Society can confer for work of an outstanding or fundamental nature in aeronautics.

British Gold Medal for Aeronautics

The British Gold Medal for Aeronautics is awarded for an achievement leading to advancement in aeronautical science.

Simms Gold Medal

The Simms Gold Medal is awarded annually for the best paper read in any year before the Society on any science allied to aeronautics, e.g., meteorology, wireless telegraphy, instruments.

The George Taylor (of Australia) Gold Medal

The Taylor Gold Medal is awarded annually, at the discretion of the Council, for the most valuable paper submitted or read during the previous session.

Wakefield Gold Medal

The Wakefield Gold Medal is awarded annually to the designer of any invention or apparatus tending towards safety in flying, and is open to members or non-members.

Society's Silver Medal

The Society's Silver Medal is awarded, at the discretion of the Council, for some advance in aeronautical design.

British Silver Medal for Aeronautics

The British Silver Medal for Aeronautics is awarded for an achievement leading to advancement in aeronautical science.

Society's Bronze Medal

The Society's Bronze Medal is awarded, at the discretion of the Council, under the same conditions as those for the Silver Medal, but for some less important advance in aeronautical design.

Wilbur Wright Memorial Premium

The Wilbur Wright Memorial Lecture is held annually, a premium of seventy-five pounds being awarded to the lecturer invited by the Council to deliver the lecture. The lecture is usually given alternately by an American and an Englishman, and is the most important aeronautical lecture of the year. It is delivered whenever possible, on the last Thursday in May of each year.

British Empire and Commonwealth Lecture

The Council of the Royal Aeronautical Society have completed the arrangements for the founding of a British Empire and Commonwealth Lecture.

The lecture, on any aeronautical subject approved by the Council, will be delivered annually in September in London, by a lecturer, chosen in alternate years from the British Dominions and Colonies and Great Britain.

The Council, by founding this British Empire and Commonwealth Lecture, are anxious to encourage new ideas and new points of view from all parts of the British Empire and Commonwealth, and to make the Lecture second only in importance to the Wilbur Wright Memorial Lecture.

The British Empire and Commonwealth Lecture will have a premium of £50 attached to it, and in the case of lecturers coming from the Dominions and Colonies an allowance will be paid towards the Lecturer's expenses.

R.38 Memorial Prize

The R.38 Memorial Prize is offered annually for the best paper received by the Society on some subject of a technical nature in the science of aeronautics, preference being given to papers which relate to airships. The prize is twenty-five guineas.

The Herbert Akroyd Stuart Lectures

Under the will of the late Mr. Herbert Akroyd Stuart a sum of £700 is held in trust by the Society for the offer of a prize every two years, for the best paper or lecture read or given before the Society dealing with the Origin and Development of Heavy-oil Aero Engines. The prize is open to members and non-members.

Edward Busk Memorial Prize

The Edward Busk Memorial Prize is offered annually for the best paper received by the Society on some subject of a technical nature in connection with aeroplanes (including seaplanes). Its value is twenty guineas.

Pilcher Memorial Prize

The Pilcher Memorial Prize is offered annually, at the discretion of the Council, for the best paper by a Student on heavier-than-air craft or any analogous subject. Its value is five guineas.

Usborne Prize

The Usborne Prize is offered annually, at the discretion of the Council, for the best paper by a Student on some subject in connection with Aero Engines. Its value is five guineas.

Major Baden-Powell Memorial Prize

The Major Baden-Powell Memorial Prize is awarded in May and December of each year to the student who is considered the best student by the examiners in the Society's Association Fellowship examinations. Its value is three guineas.

Elliott Memorial Prize

The Elliott Memorial Prize is awarded twice yearly to the apprentice at Halton who has the highest percentage of marks in the passing-out examination. Its value is 2½ guineas for each award.

R. P. Alston Memorial Prize

The R. P. Alston Memorial Prize is awarded to any Graduate or Student of the Society for work done leading to improvement in the safety of aircraft, and particularly for improvement in stability and control. Its value is approximately £5.

Branch Prize

The Council offer an annual prize of twenty guineas for the best paper read before the Branches during the previous lecture Session. The prize is open to any member of the Society or of any Branch.

Journal Premium Awards

The Council has set aside an annual sum of £250 to be given as premium awards to authors of papers published in the Journal.

AN APPRECIATION

The Council of the Royal Aeronautical Society wish to thank those Companies who, by their generous co-operation, have done so much to help in the production of the Journal.

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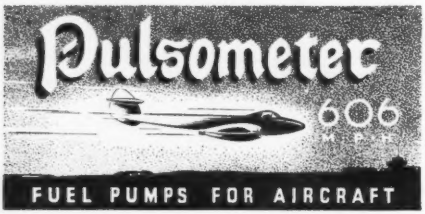

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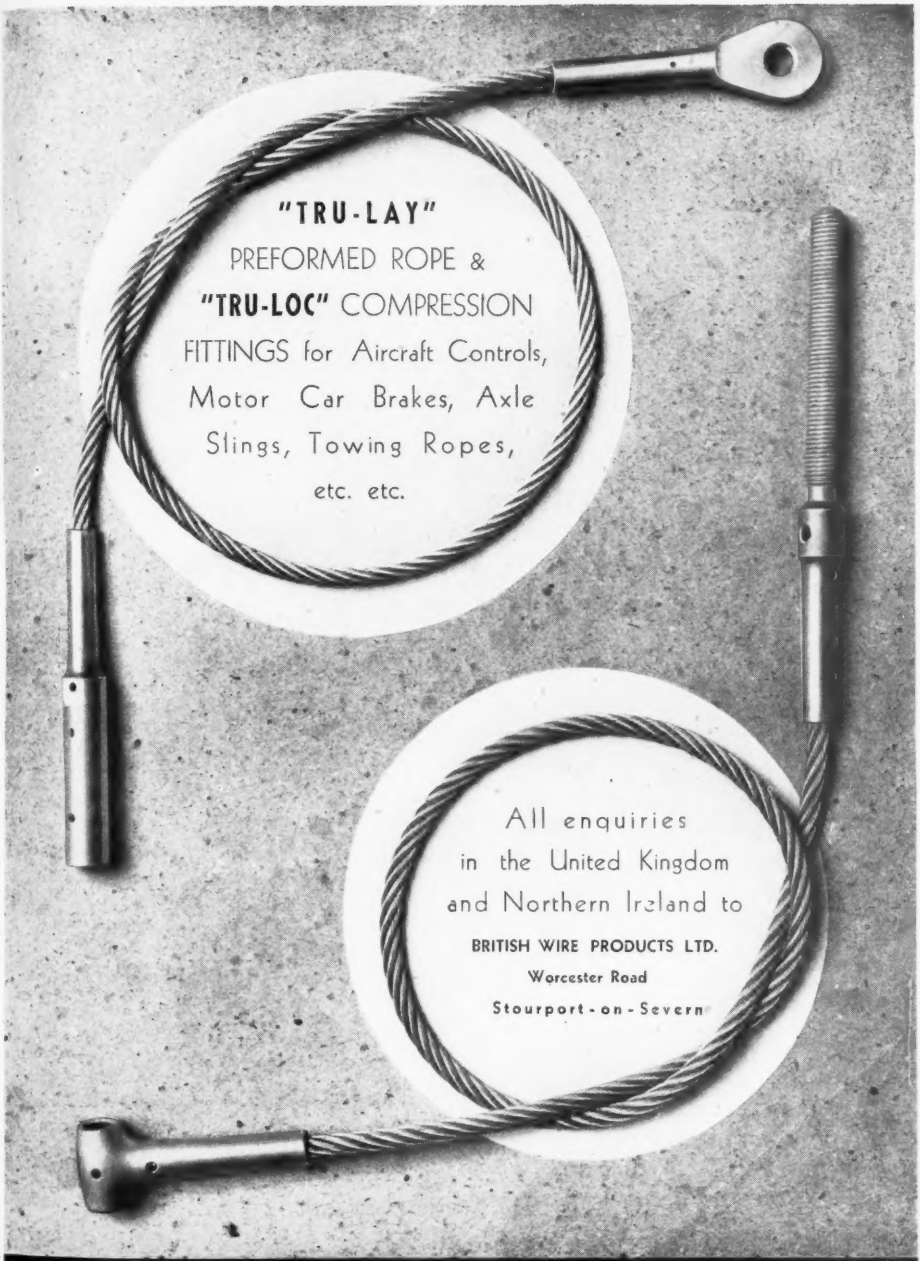

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